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# Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications

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16. ABSTRACT

This study examines and compares the outcomes of two alternate methods for controlling nonaerosol emissions of chlorofluorocarbons (CFCs). Conventional regulatory methods such as technology standards are compared with innovative methods of regulation such as use taxes or production quotas distributed through the use of marketable permits. The economic costs of each system are calculated and compared, along with a discussion of the policy issues which must be addressed when choosing one form of regulation over another.

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# ECONOMIC IMPLICATIONS OF REGULATING CHLOROFLUOROCARBON EMISSIONS FROM NONAEROSOL APPLICATIONS

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# Disclaimer

This document is a contractor's study done with the supervision and review of the Office of Pesticides and Toxic Substances of the U.S. Environmental Protection Agency. The purpose of the study was to evaluate the economic implications of alternative policy approaches for controlling emissions of chlorofluorocarbons (CFCs) in the United States.

The report was submitted in fulfillment of Contracts No. 68-01-3882 and 68-01-6111 by the contractor, The Rand Corporation and by its subcontractor, International Research and Technology, Inc. Work was completed in June, 1980.

The study is not an official EPA publication. The document can not be cited, referenced, or represented in any court proceedings as a statement of EPA's view regarding the chlorofluorocarbon industry, or the impact of the regulations implimenting the Toxic Substances Control Act.

# PREFACE

Scientific studies indicate that atmospheric emissions of certain chlorofluorocarbon chemicals (CFCs) contribute to depletion of the ozone layer that protects the earth from harmful ultraviolet radiation. Since late 1978, nearly all use of these chemicals to charge aerosol products has been banned in the United States. This report assesses the economic implications of potential regulations to limit CFC emissions from *non*aerosol applications.

This research was performed under Contracts 68-01-3882 and 68-01-6111 from the U.S. Environmental Protection Agency. It began in 1977 with a review of existing data to determine whether they were sufficient to support the economic analysis. Because these data proved inadequate, it became necessary to collect new primary data. With respect to CFC uses in refrigeration and air conditioning applications, the primary data collection was carried out by a research subcontractor, International Research and Technology, Inc. This report presents the data obtained by Rand and IR&T, together with a policy analysis performed by Rand.

This research is part of a larger program of investigation sponsored by EPA in conjunction with the Consumer Product Safety Commission and the Food and Drug Administration. Other studies are concerned with evaluating the biological and economic implications of ozone depletion. The present study focuses attention on the industries that produce and use chlorofluorocarbons, assessing the possible effects of regulation on these industries and their customers.

As a study of options for environmental policy, this research is unusual in that it investigates the potential for using economic incentives as alternatives to mandatory controls on the behavior of firms. The study examines policies that would raise the prices of CFCs and compares the costs to industry and the emissions-reducing potential of such policies with those of various mandatory controls. A further novel feature of the research is that it examines the distributive as well as the efficiency implications of policy.

Three other Rand documents containing material related to this study are also forthcoming. One is based on a briefing to EPA that sums up the study results and is recommended to readers seeking a concise, nontechnical, and policy-oriented summary of the study: Adele R. Palmer et al., *Economic Implications of Regulating Nonaerosol Chlorofluorocarbon Emissions: An Executive Briefing*, R-2575-EPA (forthcoming). Another Rand document provides somewhat greater detail on the analysis of flexible foam applications: William E. Mooz and Timothy Quinn, *Flexible Urethane Foams and Chlorofluorocarbon Emissions*, N-1472-EPA (forthcoming). Finally, Kathleen A. Wolf, in *Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production*, N-1483-EPA (forthcoming), provides an extensive description of the industries that produce the chemicals used to make CFCs.

# SUMMARY

Recent studies of atmospheric chemistry have indicated that emissions of certain chlorofluorocarbon (CFC) chemicals contribute to depletion of the ozone layer that protects the earth from harmful ultraviolet radiation.[1] As of late 1978, most uses of CFCs as aerosol propellants were banned in the United States. This study examines the economic implications of regulations on nonaerosol uses of CFCs, focusing attention on the potential costs and emissions effects of policy over the period 1980 through 1990.

The most widely used and potentially most detrimental of the CFCs are CFC-11, CFC-12, and CFC-113, and their nonaerosol applications include cushioning foams, packaging and insulating foams, industrial cleaning of metals and electronics components, food freezing, medical instrument sterilization, refrigeration for homes and food stores, and air conditioning of automobiles and commercial buildings. In 1976, the United States emitted over 300 million pounds of CFCs from nonaerosol applications—almost as much as was emitted from aerosol applications before the recent ban.[2]

A major first step in this study involved collecting primary data on CFC use levels and emissions processes and projecting future emissions through 1990. This work yielded findings that modified and extended previous studies that had focused on refrigeration applications as the most important sources of nonaerosol emissions. While the present study shows that refrigeration and air conditioning together accounted for about 33 percent of 1976 nonaerosol emissions, these applications are growing relatively slowly. By 1990, when U.S. emissions are projected to reach almost 600 million pounds in the absence of policy action, refrigeration and air conditioning are expected to account for less than 26 percent of the total. In particular, home and food store refrigeration are small contributors to emissions, both now and in the future.

Short of banning the use of CFCs, a number of technological options for reducing nonaerosol emissions have been identified by various observers. Some, but not nearly all, of these options appear suitable for implementation as mandatory regulatory controls. If implemented in 1980 and enforced through 1990, the most promising set of mandatory controls could reduce cumulative emissions over the period by perhaps 15 percent.[3] The present value of estimated compliance costs would be approximately $185 million over the period, with roughly half the costs borne by producers of flexible foams and their customers. It is anticipated that nearly all of the compliance costs would be passed through to final product consumers in the form of higher product prices. The final product price increases would be less—often much less—than five percent. With the possible exception of some small producers of flexible foams and polystyrene sheet (nonurethane foams used for packaging), plant closures and worker unemployment are not expected to result from the regulations.

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[1] See Stolarski and Cicerone (1974); Molina and Rowland (1974); Crutzen (1974); Turco and Whitten (1975); NASA (1977); and National Academy of Sciences (1976 and 1979).

[2] CFC-22, which is believed to be much less hazardous to ozone other than CFCs, is omitted from the emissions estimates cited here. This omission accounts for the absence of home air conditioners from the list of nonaerosol applications.

[3] Emissions are measured here by weighting the emissions of various CFCs according to their chlorine content. In the absence of policy action, cumulative emissions over the decade would be approximately 5.4 billion pounds, measured in CFC-113 equivalent units.

An alternative to mandatory control policy is the use of economic incentives to encourage emissions reductions. Economic incentives could take the form of a tax on CFC sales, or a sales quota, perhaps combined with marketable permits to use CFCs within the quota. The tax or quota policy can be designed to yield the same reduction in cumulative emissions as under the mandatory controls. If so, the estimated real resource costs of emissions-reducing activities induced by policy are more than 40 percent lower than those for mandatory controls. Resource costs are lower under incentives primarily because they rely more heavily on low-cost chemical substitution and less heavily on costly equipment improvements for emissions reductions. The distribution of these costs among product areas would also differ, with solvent applications carrying a larger share of the total under incentives than under mandatory controls.

Economic incentive policies can also be used to achieve greater reductions in cumulative emissions than under mandatory controls. The most stringent incentives policy analyzed here is about twice as effective as the mandatory controls. The cumulative emissions effect of the stringent policy is approximately equal to the effect of a policy that prevents growth in CFC use beyond 1980. Real resource costs under the stringent incentives policy could run as high as $600 million over the period, but are more likely to be under $300 million.

In addition to the expenses firms pay for resources to help limit CFC emissions, firms may have to pay taxes, buy permits, or pay higher CFC prices for the CFCs they continue to use under an incentives policy. These are transfer payments: They do not reflect increased use of real resources in the affected industries, and thus do not measure a sacrifice in the ability of the economy as a whole to produce goods and services. However, for the firms that pay them, the payments for taxes, permits, or higher CFC prices are an added business expense, and thus could cause increased consumer prices and could raise the risk of plant closures. Stated another way, the payments redistribute wealth away from CFC users and their customers toward the rest of the economy.

The study identifies compensation techniques that can substantially mitigate the transfers of wealth under an incentives policy. Such techniques promise to be difficult to design and implement. However, in the absence of compensation, the total present value of transfer payments between 1980 and 1990 would be very large—$1.5 billion to $1.7 billion under incentives policies that are equally effective in reducing emissions as the mandatory controls.

Ultimately, the nature of the policy choice depends upon the potential severity of the environmental damages resulting from CFC destruction of the ozone layer and the consequent level of desired emissions reductions. If relatively modest emissions reductions are acceptable, mandatory controls and economic incentives are both effective policy choices. While economic incentives substantially reduce the real resource costs of regulation, their adverse impacts on CFC users would be greater unless a compensation technique is implemented.

Given current technology, if substantial emissions reductions beyond the limited capabilities of mandatory controls are required, the relevant policy choice appears to be between outright bans on CFC use and economic incentives. CFC bans would impose exceedingly high costs on affected user groups and the economy as a whole. Economic incentives would impose lower costs on the economy as a whole, but could seriously injure CFC user industries unless wealth transfers are compensated.

This research also compares policy alternatives along other dimensions in addition to effectiveness, resource costs, and transfer payments. Among the other dimensions are ease of implementation and enforcement, the energy and environmental side effects of policy, and opportunities for easing industry's transition to regulation. No policy ranks first along all of the dimensions. Consequently, this study does not recommend a particular choice among the policy strategies. Ultimately, the choice will depend upon which dimensions of policy are deemed most important. That evaluation is left to the policymakers.

# ACKNOWLEDGMENTS

Tackling a study of this size, breadth, and complexity required learning the details of a myriad of industries and businesses—details that were often proprietary, about technical matters that were mostly unfamiliar. We found that private individuals and firms not only were cooperative, but were generous with their time and patience in explaining important details. Many companies, trade associations, and individuals went to extraordinary lengths to assist us to obtain essential information.

Naming these individuals or companies would result in a list of perhaps 400 entries, and the list would omit the names of many people who contributed indirectly through their firm's representatives or who responded anonymously to our questionnaires. Rather than perform the injustice of selecting only a few names for explicit mention, we prefer to express implicit, but heartfelt, appreciation to the many industry contributors to this study. Indeed, given the number, diversity, and geographic dispersion of the contributors, it is appropriate to view the completion of this project as a testament to the conscientiousness and sincerity of U.S. industry as a whole in recognizing its important role in helping to formulate environmental policy.

The authors also owe a substantial debt for the special efforts of several persons at Rand. Foremost, we acknowledge the pervasive contribution of the project's original director, George Eads, whose insights and talents laid a firm foundation for the research. The successful completion of the research also owes no small debt to the unflagging encouragement and support offered by two Rand managers: Mary Anderson, Head of the Divisional Support Group, and Charles Phelps, Director of the Regulatory Policies and Institutions Program. The two internal reviewers of this report, Stephen Dole and Willard Manning, showed exceptional attention to substance and detail in their comments, and deserve no blame for any remaining oversights in this final version.

The size and typographical accuracy of this document attest to the patience and skill of many secretaries: Joyce Marshall, Dorothy Gardner, Ethel Lang, and Martha Cooper. Ethel Lang and Martha Cooper deserve special recognition for their effectiveness in coordinating and facilitating the entire enterprise. Our editors Patricia Bedrosian and Janet DeLand made a substantial contribution to the quality of the presentation, in matters of both format and style.

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# I. INTRODUCTION

Recent studies have indicated that atmospheric emissions of certain chlorine-containing gases contribute to the depletion of stratospheric ozone, which shields the earth from harmful ultraviolet radiation.[1] Prominent among these gases are several chlorofluorocarbons (CFCs) that are used to manufacture a wide variety of consumer products in the United States and throughout the world.[2] In 1976, the U.S. National Academy of Sciences concluded that "selective regulation of [CFC] uses and releases is almost certain to be necessary at some time."[3]

Although ozone depletion would have deleterious consequences throughout the world, the United States has been the largest single user of CFCs and has taken the lead in acting to protect the ozone. The first regulatory steps were taken by the Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA), culminating on December 15, 1978, in a virtual ban on the use of CFCs to charge aerosol products.[4] Meanwhile, a federal interagency task force has been examining nonpropellant uses and emissions of CFCs and will present a report to the Congress in 1980 on regulation of those uses.

The 1980 report will draw on research concerning ozone depletion and related climate modification; biological and socioeconomic implications of ozone depletion; and economic implications of regulatory strategies for limiting CFC emissions from nonaerosol applications. The present study, which was commissioned in mid-1977 by EPA in conjunction with the FDA and the Consumer Product Safety Commission, considers the third topic, economic implications of regulatory strategies.

Nonaerosol applications of CFCs are diverse and ubiquitous. CFCs are used to manufacture flexible foams used in products such as furniture, bedding, and carpet underlay, and to make rigid foam insulation for buildings and refrigeration devices. Other CFC foams are used for packaging foods (e.g., egg cartons). CFCs are the refrigerants in automotive air conditioning, home refrigerators and freezers, commercial air conditioning systems, and display and storage cases for retail food stores. CFC solvents are used to clean and dry metals and electronics components and also to dry clean clothing. And CFCs are sometimes used to sterilize medical devices, to stabilize whipped dessert toppings, or to provide the gas pressure to operate boat horns and other warning devices. All these applications, and several others, are examined in this report.

This study has three major analytical components. First, it updates and extends previous estimates of CFC use and emissions through extensive primary data collection and detailed analysis of the emissions process in each product area. This

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[1] See Stolarski and Cicerone (1974); Molina and Rowland (1974); Crutzen (1974); Turco and Whitten (1975); and NASA (1977).

[2] CFCs are commonly referred to as Freon; however, Freon is a DuPont trade name and therefore is not used in this report.

[3] Continuing research has led to more detailed specification of the chlorine-containing gases of principal concern and has added other types of gases (such as bromofluorocarbons) to the list of possible ozone hazards. The National Academy of Sciences study specifically referred to fully halogenated chlorofluoroalkanes, which include the CFC that was then used as an aerosol propellant but was later banned.

[4] As of April 15, 1979, entering CFC aerosols into interstate commerce was prohibited for products that come under FDA jurisdiction.

segment of the analysis has shown that the composition of sources of CFC emissions will change over the next decade. In 1976, the emissions of CFCs from air conditioning and refrigeration devices accounted for nearly 40 percent of total nonaerosol emissions of the three most common and potentially most hazardous CFCs.[5] However, nonrefrigeration emissions sources are growing more rapidly. In the absence of regulation, the refrigeration share of emissions is expected to decline to less than 30 percent of the total by 1990.

The second major component of the analysis is an investigation of the economic properties of various technologies and procedures that industry might be able to use to reduce CFC emissions. The research team, composed of both physical scientists and economists, characterized existing technology and the economic forces that motivate choices among technologies. This investigation revealed that some emissions-control techniques have been or will soon be implemented by some CFC-using industries as a result of economic forces even in the absence of regulatory action. Consequently, our estimates of the potential for reducing emissions through regulation are lower than those that would have been obtained from a purely technical assessment of the differences between high- and low-emissions technologies.

The third major component is an assessment of the economic implications of alternative regulatory strategies. These strategies include not only regulations that would require the use of certain emissions-control techniques but also the use of economic incentives to reduce emissions. The policy alternatives are compared along a number of dimensions—costs to the economy as a whole, the distribution of costs within and among industries, and operational advantages and disadvantages of various policy mechanisms. No single policy option was found to dominate the others along all dimensions; consequently, this study does not attempt to rank policies. We merely provide information that will enable policymakers to weight the different dimensions of policies in selecting among them.

## SCOPE OF ANALYSIS

We have grouped the nonaerosol CFC applications in the United States into eight categories: (1) flexible urethane foams, (2) solvents, (3) rigid urethane and nonurethane foams, (4) automotive air conditioning, (5) chillers (i.e., large commercial air conditioning systems), (6) home refrigerators and freezers, (7) retail food store refrigeration, and (8) miscellaneous applications, including the liquid fast-freezing process and sterilants.

About a dozen chlorofluorocarbon chemicals are currently manufactured and used in the United States. The principal ones are CFC-11, CFC-12, and CFC-113 (the numerical suffixes identify their chemical formulas). CFC-114, which until recently was used principally as an aerosol propellant, is also used to a very limited extent in these products. There are also some CFC chemicals that are made by combining other CFCs in various proportions; the most prominent of these are CFC-500 and

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[5] These are CFC-11, CFC-12, and CFC-113. It should be noted that most previous studies of CFC emissions exclude CFC-113 even though it is fully halogenated and its use is rapidly increasing.

CFC-502.[6] At least 85 percent of the total annual use of these CFCs for nonpropellant applications is reflected in our analysis.

Most other CFC emissions analyses—including the 1976 and 1979 studies by the National Academy of Sciences—have failed to consider CFC-113 and CFC-114. However, because of rapid growth in the solvents market for CFC-113, this has become a significant source of emissions, and current scientific analyses indicate that CFC-113 is about as hazardous to the ozone (per pound of emissions) as CFC-12.[7]

Another chlorofluorocarbon, CFC-22, is widely used in home and supermarket air conditioning systems; this chemical accounted for nearly one-fourth of total domestic CFC use for nonpropellant applications in 1976. However, CFC-22 is not fully halogenated (i.e., it contains a hydrogen atom), and models of atmospheric chemistry indicate it is only one-tenth to one-fifteenth as hazardous to the ozone layer (per pound of emissions) as the CFCs listed above. Therefore, we have not treated CFC-22 as a principal ozone hazard, and home and supermarket air conditioning systems are not included in the list of analyzed products. CFC-22 has been cited as a potential substitute for other, more hazardous CFCs in the refrigeration product areas we have analyzed, however, and this possibility is examined in this report.

This study estimates CFC use and emissions from 1970 to 1976 (the last date for which historical data were available at the start of this research), for each product area and CFC. Projections of annual use and emissions extend through 1990, the most distant date for which predictions of future product market conditions are available from industry and published data sources. Projections of future use and emissions in the absence of regulation form a baseline time profile of emissions against which we measure reductions in emissions that might be generated by regulatory action.

For each category of nonaerosol applications, the study identifies feasible technical options for limiting emissions. When adequate data are available, each technical option is evaluated in terms of its cost to industry, its effectiveness in limiting emissions when properly implemented, the length of time required to implement the option, the CFC price required to make use of the option cost-effective to industry, and the ease with which the option could be enforced if required by regulation in the absence of increased CFC prices.

The technical feasibility and cost of some technical options for emissions control are not well known. Some options are still on the drawing boards, while others have been so little used that their costs in an expanded market are not known. Given these uncertainties, prudence suggests that these options should be viewed skeptically, both as candidates for mandatory controls and as likely outcomes of economic incentives policies.

More generally, this analysis has taken a cautious approach in its treatment of uncertainty. By design, our predictions of policy effects may tend to understate potential emissions reductions and overstate costs to industry.[8] However, the analytical procedures and assumptions that lead to cautious predictions are specifically designed to be evenhanded in the treatment of alternative policies, and the resulting comparison among policy options should not be affected.

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[6] CFC-500 is a blend of CFC-12 and FC-152a (a fluorocarbon that contains no chlorine). CFC-502 is a blend of CFC-22 and CFC-115.

[7] Personal communication with Dr. M. J. Molina, University of California at Irvine.

[8] In contrast, our baseline emissions projections are not particularly cautious, but are a "most likely" outcome given what firms told us about their own plans for the future.

The study explores the implications of two general policy strategies, those that set specific standards for the way CFCs are used or emitted (mandatory controls), and those that provide economic incentives for reducing use and emissions. The mandatory control options necessarily differ from one product area to another, while economic incentive policies can be applied to the CFC market as a whole, by effectively raising the prices at which CFCs can be purchased.

Evaluation of the health and environmental effects of ozone depletion is beyond the scope of this study, and we have not attempted to weigh the costs of regulation against health and environmental benefits. Instead, we identify mandatory control policies that could be expected to reduce CFC emissions between now and 1990 without seriously curtailing the availability of the services provided by the final products made from CFCs. These policies establish a benchmark of cumulative emissions reductions over the next decade.[9] We have calculated the costs of these mandatory controls and compared them with the costs that would be incurred under economic incentives policies designed to match or improve upon the benchmark level.

This study was not mandated to examine potential bans on production of certain CFCs or their use in particular applications. However, it is possible to draw some qualitative conclusions about the implications of such bans, based upon the analyses and data presented here. These inferences are noted in the concluding section of this report.

Programs to encourage voluntary emissions reductions are not examined in detail, though they are discussed briefly in the concluding section. Historically, commercial firms have sometimes acted in the public interest, even when it has cost them something to do so. However, it is difficult to predict the extent to which industry would voluntarily undertake actions to reduce CFC emissions, so we have cautiously assumed that firms will voluntarily take only those actions that are already cost-saving or nearly so. Logically, the effects of such cost-saving actions are built into the baseline use and emissions profiles presented in this study.

Policy alternatives are evaluated here primarily in terms of their potential effects on CFC users' capital investment and production costs, and on consumer prices. The policies may also affect employment, energy use, or worker exposure to hazardous materials that might be substituted for CFCs and, where possible, this study identifies these factors and other possible side effects as well as the basic economic implications of regulation.

Any policy that reduces CFC use below the baseline projection implies that the CFC producers will face smaller markets for their products than they would in the absence of regulation. Appendix A reports the reductions in CFC for 1980 and 1990 under various policy scenarios.[10] Some, but not all, of the polices would cause an initial cutback in annual production below 1979 levels. However, none of the policy scenarios that are analyzed quantitatively would cause annual cutbacks below 1979 levels throughout the entire period 1980 through 1990. Consequently, the likelihood of CFC production facility closures is substantial only in cases where the long-term profitability of continued operation is critically dependent on achieving the baseline level of CFC market growth. We do not have sufficient data on CFC plant capacity utilization and profitability to make a judgment about the likelihood of CFC plant closures.

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[9] As explained later in this section and in Sec. II, scientific models indicate that cumulative emissions over a decade is an appropriate measure of the effectiveness of a policy in protecting the ozone layer.

[10] Another Rand document (Wolf, 1980) details the relationships between baseline and regulatory scenario output levels for CFCs.

## SOURCES OF INFORMATION

In a preliminary stage of this research, we reviewed the existing CFC studies, evaluating them as a source of data for policy assessment. We found that historical data were incomplete and often conflicting, and that projections of future CFC use and emissions were virtually nonexistent. Consequently, we developed our own data base from interviews and surveys of industry contacts; in the refrigeration product areas, data collection was performed by a research subcontractor, International Research and Technology Corporation (IR&T). The information from all sources was summarized in written reports, which were submitted to the sources for review and revision. We then used this new data base to prepare use and emissions profiles and to evaluate the implications of various policy candidates.[11]

## OVERVIEW OF RESULTS

The following discussion summarizes the analyses and findings from a complex research project, and thus necessarily skirts certain issues and avoids certain details. Notes to the text, as well as the Table of Contents, identify sections of this report that deal with individual matters in far greater detail.

### Use and Emissions

Table 1.1 summarizes the use and emissions estimates obtained in this study for 1976 and 1990, combining all the CFCs (except CFC-22). A more detailed breakdown of these data is given in Sec. III. Emissions are projected to more than double by 1990, led by growth in rigid foam, solvent, and flexible foam applications. Annual worldwide emissions, which have been a little more than twice the U.S. level, could grow proportionately, though this possibility is not supported by detailed analysis from this study. These growth rates are considerably above the zero-growth rate being assumed by many of the current scientific studies that are attempting to predict the extent of climatic change and ozone depletion due to CFC emissions. We emphasize that the estimated growth rates to 1990 cannot be projected to continue beyond that year. The CFC applications most responsible for the cur-

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[11] Although the refrigeration product area analyses are based on the IR&T data, some revisions have been made. Evident errors in data calculation have been corrected, and in some instances, we reinterpreted the implications of IR&T data or reevaluated the feasibility of various emissions-control strategies.

## Table 1.1

## ESTIMATED CFC USE AND EMISSIONS FROM NONAEROSOL APPLICATIONS (EXCLUDING CFC-22), 1976 AND 1990[a]

(Millions of pounds)

| | 1976 | | 1990 | |
|---|---|---|---|---|
| Analyzed Applications | Use | Emissions | Use | Emissions |
| Flexible foam | 34 | 34 | 72 | 72 |
| Solvents | 69 | 69 | 147 | 147 |
| Rigid foams | | | | |
| Urethane | 37 | 14 | 159 | 59 |
| Nonurethane | 23 | 19 | 67 | 54 |
| Mobile air conditioning | 90 | 76 | 125 | 122 |
| Other refrigeration | | | | |
| Chillers | 13 | 12 | 20 | 17 |
| Home refrigerators and freezers | 6 | 5 | 9 | 7 |
| Retail food devices | 11 | 10 | 10 | 9 |
| Miscellaneous | | | | |
| LFF | 6 | 6 | 15 | 15 |
| Sterilants | 13 | 13 | 40 | 40 |
| Other | 4 | 4 | 15 | 9 |
| Total | 306 | 262 | 679 | 551 |
| Other applications | 51 | 51[b] | 47 | 47[b] |

[a] Calculations were performed from data provided by industry and published sources, as explained in Secs. III.A through III.H. Annual use does not necessarily equal annual emissions because some CFCs are banked in final products and released slowly over time.

[b] Although some of the products in this category may bank the CFC, estimated emissions figures assume all CFCs are promptly emitted.

rent high growth rates are in a phase of increasing market penetration, as a result of either increased use of final products or increased use of CFCs in manufacturing those products. By 1990, penetration should be complete in most existing markets, so the CFC use growth rate should slow to approximately that of the GNP, unless significant new uses of CFCs are developed in the next decade. Moreover, easily extracted fluorine is expected to become scarce toward the end of this century, which will increase the prices of CFCs and provide incentives to develop new technologies that are less CFC-oriented.

Table 1.1 shows that the contribution to emissions made by home appliances and retail food store refrigeration is relatively minor. These products are frequently mentioned at the forefront of discussions of the prospects for reducing CFC emissions, implying that solutions to the ozone depletion problem hinge upon sacrificing food storage or developing new refrigeration technology. The data clearly do not support such contentions.

The projections of annual emissions for 1980 through 1990 in the absence of regulatory policies represent the baseline time profile of emissions against which policy effects are measured in this study. Hence, a "reduction in emissions" is achieved if the time profile of emissions under regulation lies below the baseline time profile. None of the policy alternatives considered here would result in negative average rates of growth in emissions for the decade as a whole.

## The CFC "Bank"

As shown in Table 1.1, not all of the CFCs used in a year are emitted in that year. Some products are made by confining the CFC within the product, and the confined CFC may be emitted only slowly over time or may be retained until the product ruptures, perhaps at the time of disposal. We refer to the CFC contained in a stock of final products as the CFC "bank." (Emissions that occur as soon as the CFC is first used are referred to as "prompt" emissions.) A substantial degree of banking occurs in rigid urethane and some nonurethane foams, mobile air conditioners, chillers, retail food store refrigeration devices, and home refrigerators and freezers.

Table 1.2 reports our estimates of the size of the CFC bank by product area for 1976 and 1990. Additions to the bank through growth in final product output are far larger than emissions from the bank over this period. The bank will nearly triple by 1990, most of the increase being attributable to rigid foams. Thus, even if all CFC use were banned by 1990, a large amount of emissions would still occur over the following decade.[12] The eventual emissions from the 1990 bank alone would about equal the total cumulative emissions for 1976 through 1981.

## Mandatory Control Options

All of the technical options for emissions control identified in this study were tested against three criteria, which they had to satisfy in order to be included in the "benchmark" set of mandatory controls. First, the option had to be enforceable. If an option would be so costly to industry that it would present strong incentives for evasion, and if it would have to be monitored frequently and at many sites, then the cost of effective enforcement would be so high that such an option is herein deemed unenforceable. For example, technical options that were excluded from the benchmark set on this basis include recovery of CFC refrigerant from home appliances, chillers, automotive air conditioners, or retail food refrigeration systems that are being scrapped. Some other unenforceable options are noted below, and all are discussed in the product area sections of this report.

The second criterion was that data on the technical feasibility and cost of an option had to appear reliable and internally consistent. Many of the options ex-

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[12] And not all of the bank would be emitted within that decade. Emissions from rigid foams would continue for many decades.

Table 1.2

Estimated Size of the CFC Bank in 1976 and 1990 (Excluding CFC-22)[a]

| Product Area | CFC Bank (millions of lb) 1976 | 1990 |
|---|---|---|
| Rigid foams | | |
| Urethane | 230 | 1,156 |
| Nonurethane | 20 | 135 |
| Mobile air conditioning | 222 | 384 |
| Other refrigeration | | |
| Chillers | 59 | 89 |
| Home refrigerators and freezers | 86 | 104 |
| Retail food store devices | 56 | 81 |
| Total | 673 | 1,949 |

[a] See Secs. III.A through III.H for calculations and data sources.

cluded on this basis involved CFC uses in miscellaneous products and would result in only small reductions in emissions even if they proved effective and enforceable. The options excluded on the basis of poor data that could have contributed significantly to emissions reductions by 1990 are primarily related to automotive air conditioning products, and most of these options involve the use of such new and unproved technologies that further assessment would be required before regulations could be instituted.

The third criterion for the benchmark control candidates was designed to permit valid comparisons between economic incentives and mandatory controls; it concerns the anticipated timing of the costs and emissions effects of the proposed options. Most of the technical options that involve substituting an alternative refrigerant in refrigeration or air conditioning applications would require some research and development, followed by major retooling, and then followed by substantial turnover of the existing stock of refrigeration devices before any effects on emissions would become noticeable. Given the 1990 horizon for the quantitative policy comparisons, almost all of the costs and virtually none of the emissions benefits of such options would be observable in the benchmark analysis. Consequently, the comparison between mandatory controls and economic incentives would yield misleading and arbitrary results. The longer-run implications of incorporating slowly maturing technical options in a regulatory strategy are explored in the product area sections of this report but are not reflected in the analysis of benchmark outcomes.

The technical options that met all three criteria are listed in Table 1.3. These benchmark control options involve three emissions-reduction techniques. One is recovery and recycle, which captures CFCs that would otherwise be released to the atmosphere and returns them to use in place of virgin chemicals. Recovery and recycle appears to be a feasible option for producers of flexible foam and thermoformed polystyrene sheet, a rigid nonurethane foam used in packaging applications. The second technique is the imposition of equipment standards for users of solvents in industrial cleaning and drying. These standards would specify design features for cleaning and drying equipment that would limit the escape of CFC vapors into the atmosphere. The final technique is substitution of less-hazardous CFCs for the CFCs that are currently used. Substitution of CFC-22 for CFC-12 as the gas used in testing chillers and retail food store refrigeration systems would reduce emissions of CFC-12. Retail food store refrigeration systems designed for medium-temperature (nonfreezing) applications could be charged with CFC-502 instead of CFC-12.[13] Thus, the benchmark controls would reduce emissions of the most hazardous CFCs from certain applications in six of the major product areas under investigation.

Table 1.3

**BENCHMARK MANDATORY CONTROL OPTIONS**

- Flexible foams: recovery and recycle of CFC-11 in slabstock and molded flexible foam plants.
- Solvents: equipment standards for users of CFC-113 in cleaning and drying applications.
- Rigid foams: recovery and recycle of CFC-12 in thermoformed extruded polystyrene sheet plants.
- Chillers: conversion to CFC-22 test gas at manufacture.
- Retail food refrigeration: conversion to CFC-22 test gas in manufacture.
- Retail food refrigeration: conversion to R-502 refrigerant in medium-temperature (nonfreezing) systems.

Two technical options that were excluded from the benchmark control candidates could result in substantial emissions reductions under an economic incentive policy. One is substitution of methylene chloride for CFC-11 in flexible foam manufacture. This option was omitted because it does not pass the enforceability test. Not all foams can be made with methylene chloride, so regulatory exemptions would be necessary to permit all types of existing foams to remain on the market. Given the several hundred production sites for foams and the ease with which production can be converted back and forth between CFC and methylene chloride, it would be extremely difficult to ensure that CFC was being used only for the exempted foams. In contrast, economic incentives could make it profitable for many foamers to use methylene chloride instead of CFC-11. Moreover, our analysis anticipates that a

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[13] This change would not require extensive research and development or industry retooling and thus would yield most of its emissions effects by 1990.

CFC recovery and recycle mandate would induce some foamers to convert to methylene chloride rather than comply directly with the regulation. Thus, even though methylene chloride substitution is not one of the benchmark controls, some substitution is expected to occur if the benchmark controls are implemented.

The second option that is notably absent from the benchmark candidates is substitution of other solvents for CFC-113. Regulatory exemptions would be necessary in particular solvent applications where substitution is not feasible. As in the case of methylene chloride substitution in flexible foams, exemptions facilitate evasion of regulation, making enforcement difficult and costly. Perhaps more important, many of the potential solvent substitutes for CFC-113 are currently thought to be possible health or environmental hazards. A regulatory decision to require increased use of one or more of the alternative solvent substitutes would necessitate weighing the risks of ozone depletion against other hazards. The doubtful prospects for a near-term regulation mandating solvent substitution make it a poor candidate for the benchmark controls.

Like bans on the use of CFCs, policy options to eliminate the existing CFC bank through retrieval or replacement of the existing stock of CFC-holding products are excluded from this report, reflecting a judgment on the part of EPA that such policies would be far too costly to implement. Regulations concerning newly produced CFC-holding products, such as requiring the use of a different refrigerant in new refrigerators and freezers, are considered, but few such options appear in the benchmark controls because most of their emissions effects would occur after 1990.[14]

## Estimated Effects of Mandatory Control Options

To analyze the implications of mandatory controls or economic incentive policies, it is necessary to specify the year of implementation. In order that the outcomes of policy could be revealed over as long a period as possible, given the 1990 horizon of our data base, we have assumed that the benchmark controls would be implemented in 1980 and enforced through 1990. For purposes of comparison, economic incentives are also assumed to be implemented in 1980. However, using a later implementation date would not jeopardize the qualitative results of the comparison of the two policy strategies, provided the same implementation date would apply to either strategy.

Furthermore, to compare alternative policies, it is necessary to establish a common measure of effectiveness in protecting the ozone layer. We do this first by measuring the emissions effects of each policy in terms of "permit pounds." The permit-pound measure weights the CFCs so that one permit pound of any CFC has the same chlorine content as a pound of CFC-113. Because chlorine content is a major factor in determining the ozone depletion potential of fully halogenated CFCs, the permit pound is an appropriate measure for comparing the ozone protection afforded by various policies.[15]

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[14] See Sec. II for a dicussion of why new source performance standards for manufacturing processes are not treated as candidates for the benchmark controls.

[15] The multiplicative weights are: 1.36 for CFC-11; 1.03 for CFC-12; .26 for CFC-502; and 1.00 for CFC-113. The weight for CFC-502 reflects the chlorine content of its CFC-115 component and one-tenth

Second, the overall environmental protection achieved by a policy is measured by its impact on cumulative emissions levels from 1980 through 1990. Information supplied by EPA indicates that the ultimate damage to the ozone layer is independent of the timing of emissions over periods as short as one decade. (See Sec. II.)

Table 1.4 summarizes results of the analysis of the benchmark mandatory controls. The cumulative emissions reductions are measured in pounds of CFCs and, alternatively, in permit pounds. Note that conversion from CFC-12 to CFC-502 increases CFC-502 emissions. The permit-pound measure of this effect reflects the estimate that a pound of CFC-502 is only about one-fourth as hazardous to the ozone layer as a pound of CFC-12.

Table 1.4

ESTIMATED EFFECTS OF THE BENCHMARK MANDATORY CONTROLS[a]

| Product Area | CFC | Annual Reductions in Emissions[b] (millions of lb) | | 1980-1990 Cumulative Emissions Reduction (millions) | | 1980-1990 Cumulative Compliance Costs[c] (millions of $) |
|---|---|---|---|---|---|---|
| | | 1980 | 1990 | CFC Pounds | Permit Pounds | |
| Flexible foams | CFC-11 | 26.5 | 40.5 | 368.5 | 501.2 | 93.3 |
| Solvents | CFC-113 | 10.0 | 32.5 | 185.7 | 185.7 | 45.7 |
| Rigid foams | CFC-12 | 7.2 | 11.3 | 103.0 | 106.1 | 38.8 |
| Retail food refrigeration | CFC-12 | 1.0 | 4.0 | 22.9 | 18.3 | 7.3 |
| | CFC-502 | -0.7[d] | -3.9[d] | -20.4 | | |
| Chillers | CFC-12 | 0.1 | 0.1 | 1.0 | 1.0 | 0.1 |
| Total | Non-CFC-22[e] | 44.1 | 84.6 | 660.7 | 812.3 | 185.3 |

[a] Detailed calculations are presented in Secs. III.A. through III.G and IV. Components might not sum to totals because of rounding.

[b] Baseline use and emissions in CFC pounds are shown in Table 1.1. Baseline use measured in permit pounds would be 454.9 millions in 1980 and 784.4 millions in 1990, for a cumulative total of 6.7 billions over the period 1980 through 1990. Baseline cumulative emissions are 5.4 billion permit pounds.

[c] Cumulative compliance costs are the sums of annual compliance costs in constant 1976 dollars discounted at 11 percent per year.

[d] The negative signs for CFC-502 emissions reductions indicate that those emissions would increase under the mandatory control options.

[e] The totals for non-CFC-22 exclude the 48.8 percent of CFC-502 that is composed of CFC-22.

Compliance costs are the costs of resources used in the industry activities that reduce CFC emissions. For example, a firm's expenses to purchase and operate CFC recovery and recycle equipment are measured by compliance costs. The cumulative

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the chlorine content of its CFC-22 component. It is possible to adjust the weights to specify permit pounds using any CFC as the base, but all calculations in this report use CFC-113 as the base. The use of chlorine content to weight emissions of different CFCs was recommended by EPA, and was accepted by Dr. M. J. Molina as a reasonable approximation to the relative ozone hazards implied by current scientific models.

compliance cost estimates are the sums of annual compliance costs (in constant 1976 dollars), discounted to 1980 at 11 percent per year.[16]

The economic analysis indicates that compliance costs would be passed through to consumers in the form of modest increases in final product prices (less than five percent in all cases for which data are available). The data in Table 1.4 reflect an assumption that the anticipated price increases will not seriously restrict the market for any of the final products made by CFC-using firms. A possible exception is the market for rigid foams (polystyrene sheet) used in packaging applications, where paper and cardboard are closely competitive products. Because this type of foam is a small component of the rigid foams product area, revising the assumption for that case would only slightly increase the emissions reductions and reduce the compliance costs shown in the table. It should be noted, however, that rigid packaging foam is a product for which any regulatory action, whether mandatory controls or economic incentives, increases the risk of plant closures. (See Sec. III.C.)

The estimates of emissions reductions and compliance costs presume that no new regulatory restrictions will be placed on chemicals that might be substituted for CFCs.[17] The effects of this presumption are not trivial. In flexible foams, for example, 40 percent of the emissions reduction shown in Table 1.4 is achieved by some smaller producers who find it less costly to convert to methylene chloride than to recover and recycle CFC-11.

Overall, the benchmark mandatory controls would reduce cumulative permit pounds of U.S. nonaerosol emissions by about 15 percent between 1980 and 1990 (inclusive).

## Economic Incentives Policy Options

The economic incentives policies studied here function by raising the prices of newly produced (virgin) CFCs. With increased CFC prices, some users would find it cost-saving to recover and reuse CFCs that would otherwise be emitted, to substitute alternative chemicals for CFCs, to purchase equipment that reduces CFC losses to the atmosphere, or to make other changes in their production or servicing practices. The CFC prices at which various technical options become cost-saving for various users are predicted by the CFC demand analyses presented in the product area sections of this report.

As Secs. IV and V explain, CFC prices could be raised either through an excise (sales) tax, which the user would pay in addition to the CFC supplier's price for each pound of CFC purchased, or through imposition of a quota on total CFC sales. Under a quota system that effectively restricts the availability of CFCs, some mechanism is necessary for allocating the available supplies among users. As Sec. V explains, a reliable way to assure that the allocation is economically efficient is for the regulatory body to issue marketable permits for CFC use.[18] The permits would resemble ration coupons and would have a designated face value authorizing purchase (or sale) of certain amounts of alternative CFCs during a specified time period. CFC users would obtain newly issued permits and could buy and sell permits among themselves.[19] Thus, the market for permits determines their price. A user wishing to buy CFCs would have to turn in permits he has acquired as well as pay the producers' CFC prices.

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[16] Section II explains the choice of 11 percent for cost discounting and zero percent for emissions discounting.

[17] All existing OSHA, EPA, and other regulations are presumed to remain in effect.

[18] Section V also discusses the implications of quotas without permits.

On a given CFC demand schedule, a particular CFC price corresponds to a particular level of CFC use. In principle, therefore, a tax that yields a targeted level of CFC use equals the permit price for a quota set equal to the use target. Consequently, the quantitative analysis described here treats the two incentives policy techniques as identical. However, Secs. V and VI discuss operational differences between tax and permit quota approaches.[20]

All of the economic incentive policy designs specified for the quantitative analysis assume that all applications of fully halogenated CFCs would be subject to the policy. This feature promotes economic efficiency by encouraging pursuit of the least costly combination of emissions-reducing activities among all product areas and all CFCs to achieve a given goal. It is also especially valuable in providing incentives for new technology development in product areas where no emissions-reducing options appear to exist. Not incidentally, widespread coverage by a permit policy helps to ensure against a very small number of firms attempting to corner the market for CFC permits. Finally, it is less costly to administer an economic incentive policy that does not exempt certain users.[21]

While all applications would be subject to the policy, the tax or permit price would vary among CFCs, depending on the CFC's potential for environmental damage per pound of emissions. This feature provides greater incentives for reducing emissions of the most hazardous CFCs, including substitution of less-hazardous CFCs where that is technologically feasible. The desired price differentials are achieved by specifying a tax rate or permit price per "permit pound" as defined above. For example, a tax rate of 10 cents raises the price of CFC-113 by 10 cents but raises that of CFC-11 by about 14 cents; similarly, a permit purchased for 10 cents would allow the use of one pound of CFC-113 or about 0.74 pounds of CFC-11.

When the product area demand schedules for a given year are specified in terms of permit pounds and are aggregated, the year's overall demand curve looks like the curve in Fig. 1.1, which shows the demand schedule for 1980. The CFC producers' supply prices have been subtracted from the user demand price, so the vertical axis is specified in terms of a price increment that could be established by policy action. The points in the figure represent our point estimates of CFC use and price combinations, while the dashed curve is a continuous approximation illustrating the point estimates. Section IV details the derivation of the demand schedules and explains how less cautious assumptions would alter the demand schedules and hence the estimates of policy effects.

Figure 1.1 shows that CFC demand is responsive to price. The distribution of inducement prices for emissions reductions is such that many different product areas would participate in such activities throughout the price range, as indicated

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[19] Section V discusses the option of also allowing the CFC producers to buy and sell permits.

[20] In practice, the two policies can be expected to yield different outcomes, partly because there is uncertainty about the precise relationship between CFC prices and quantities demanded, and partly because taxes usually cannot be changed without legislative action and thus are relatively inflexible over time. Marketable permits can more easily yield permit prices that vary over time due to variations in the annual quota level.

[21] The implications of exemptions are discussed in Sec. V.

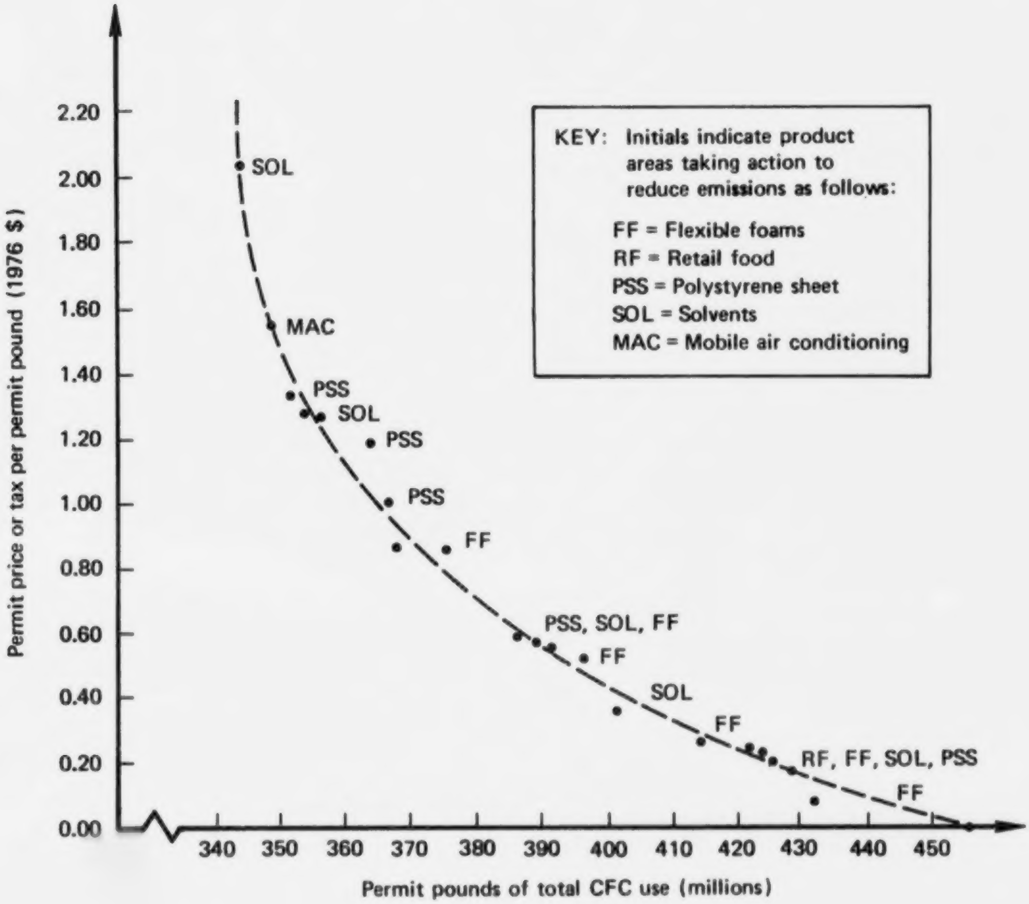

Fig. 1.1—1980 demand schedule for use of fully halogenated CFCs

by the product area labels in the figure. For example, a price increment of 25 cents per permit pound would induce producers of retail food refrigeration systems, flexible foams, and some types of rigid foams, as well as solvent users, to undertake emissions-reducing actions.[22] The CFC demand curves for years other than 1980 also reveal a mix of price responses across product areas, though of course the curves shift to the right and change shape somewhat to reflect growth in demand in the various product areas.[23]

Because virtually all the CFC used is ultimately emitted, limiting use limits emissions. As a practical matter, the amount of CFC going into the CFC bank is very insensitive to CFC prices, so the price effects we estimate appear primarily in the prompt-emitting applications. Consequently, a price increase that reduces use in a given year will reduce emissions in that year by almost the same amount. The demand curves can therefore be used to determine the amount of emissions reduction in a given year that would be induced by raising prices by a certain amount in that year.

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[22] A 25 cent price increment per permit pound translates into a 25 cent increment per pound of CFC-113, a 26 cent increment for CFC-12, and a 34 cent increment for CFC-11. In 1976, CFC supply prices ranged from about 34 cents (CFC-11) to $1.20 per pound (CFC-152a).

[23] The CFC demand schedule point estimates for 1980 and 1990 are presented in Appendix C.

During the first year of implementation, 1980, the benchmark mandatory controls would reduce use by nearly 58 million permit pounds (thus reducing emissions by 54 million permit pounds). From Fig. 1.1, the same reduction would be induced by a price increase of about 50 cents per permit pound. Larger price increases would yield even greater emissions reductions. If prices were increased by $2.20 per permit pound, 1980 use could be reduced by roughly 111 million permit pounds. Our demand analysis does not evaluate the effects of CFC price increases above $2.20 per pound, in part because higher prices would not be necessary to achieve the most severe emissions reductions contemplated in this study, and in part because higher prices seriously threaten to put many firms out of business or even to eliminate entire product areas.[24]

Three economic incentive policy scenarios are examined in this report. The first, called the "benchmark-equivalent" scenario, would achieve approximately the same cumulative emissions reduction as the benchmark mandatory controls. The second, called the "low-growth" scenario, minimizes the average rate of growth in CFC use over the coming decade, subject to a maximum price increment of $2.20 per permit pound in 1990; this policy would be only slightly more effective than the benchmark-equivalent policy and is not referenced further in this overview, but the low-growth scenario is used in Sec. IV to illustrate the cost implications of attempting to regulate annual growth rates rather than cumulative emissions. Finally, the third scenario, "zero-growth," would have the same effect on cumulative emissions as prohibiting growth in annual CFC use beyond the 1980 level.[25]

A given reduction in cumulative emissions can be obtained through many different combinations of annual price increments. For example, the price increment could be set in 1980 and maintained at the same level (in constant dollars) every year through 1990, or the increment could be set at a lower level in the initial year but raised gradually over the period. While both types of policy design would have the same cumulative emissions effect, the discounted cumulative costs to industry would differ. The results cited in this overview reflect only policy designs in which the price increment is held constant; however, Sec. IV indicates that costs to industry can be slightly reduced by using a price increment that increases at a constant rate of 11 percent per year—or noticeably increased by using a price increment that starts lower but rises much more rapidly.

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[24] Section II explains that our CFC demand models assume final product demand schedules are perfectly inelastic. The assumption becomes less acceptable as the CFC price rises, and we do not recommend using our models for permit prices or taxes much above $2.20 per permit pound.

[25] As examined here, the zero-growth policy would not actually hold annual use constant because that proves to be much more costly than a policy that allows annual use to vary while achieving an equivalent cumulative emissions reduction.

## Estimated Effects of Economic Incentives Policies

Mandatory controls require firms to use real resources to implement and operate technical options for emissions control. Real resource costs, or "compliance costs," for technical options also arise under economic incentives policies. In addition, economic incentives cause firms to make tax or permit payments for the CFCs that continue to be used. The tax or permit payments are wealth transfers that leave the affected firms and enter the economy elsewhere; unlike compliance costs, transfers do not cause the economy as a whole to sacrifice the production of other goods and services.[26] Because compliance costs and transfer payments have different implications, these factors are treated separately in this analysis.

**Compliance Costs.** Economic incentive policies impose lower costs on the economy as a whole than the benchmark mandatory controls, even when they achieve the same cumulative emissions reductions. The benchmark-equivalent scenario requires a constant price increment of about 50 cents per permit pound and yields estimated cumulative compliance costs only 58 percent of those estimated for the benchmark controls. Using marketable permits to achieve this outcome would require setting a 1980 quota of 396 million permit pounds (13 percent below 1980 baseline use) and allowing the quota to increase by about 5.6 percent per year through 1990.

The reasons for lower compliance costs under economic incentives can perhaps best be illustrated by reference to an example of policy responses in the solvents product area. Under mandatory controls, most solvent users would have to invest in more conservative equipment; the majority of solvent users would comply directly with the regulation because the equipment investment is too small to make substitution of a different solvent a more cost-effective alternative. In contrast, under economic incentives the price of the CFC-113 purchased by solvent users would increase enough to encourage some of them to substitute an alternative solvent. This leads to much larger solvents emissions reductions under incentives than under controls, which in turn means that some CFC users in other industries (particularly in rigid packaging foams) for which mandatory controls would be very costly do not have to contribute as much to emissions reductions. Hence, because incentives induce firms to use the least costly combination of technical options for limiting emissions, the overall cost of achieving the benchmark level of emissions reduction is lower under incentives than under mandatory controls.

Given the very cautious assumptions embodied in the demand-curve analysis, the zero-growth scenario implies very high compliance costs. The price increment would have to be maintained above $2.00 per permit pound throughout the period, and cumulative compliance costs would be nearly $600 million.

The cautious assumptions that lead to high costs for zero growth partly reflect a lack of data on the costs of several apparently feasible technical options in various product areas (especially in miscellaneous products). If these options prove to be as sensitive to CFC prices as the options for which cost data are available, the cumulative emissions effect of zero growth would be achievable with a constant price increment of 64 cents per permit pound, thus doubling the cumulative emissions reduction of the benchmark mandatory controls while generating cumulative compliance costs only one-and-a-half times as high.

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[26] For further discussion of this point, see Sec. II.

Table 1.5 summarizes results from the three incentive policy scenarios and compares them with the benchmark controls.

Table 1.5

SUMMARY COMPARISON OF POLICY OPTIONS[a]

| | Emissions Reduction (millions of permit pounds) | | | Compliance Costs (millions of 1976 $) | | |
|---|---|---|---|---|---|---|
| Policy Options | 1980 | 1990 | 1980-1990 Cumulative | 1980 | 1990 | 1980-1990 Cumulative[b] |
| Mandatory Controls | | | | | | |
| Benchmark candidates | 54 | 102 | 812 | 21 | 37 | 185 |
| Economic Incentive Policy Scenarios (Constant-Price Increment Designs) | | | | | | |
| Benchmark equivalent | 55 | 102 | 816 | 12 | 22 | 108 |
| Zero growth: | | | | | | |
| Cautious assumptions | 108 | 190 | 1,602 | 68 | 122 | 600 |
| Alternative assumptions | 108 | 195 | 1,625 | 31 | 54 | 268 |

[a] Calculations are explained in Sec. IV.

[b] The 1980-1990 cumulative figure is the present value of annual compliance costs, discounted at 11 percent.

**Transfer Payments.** The size of transfer payments depends on the way in which an economic incentives policy is implemented. The payments are largest if users must pay taxes, purchase permits, or pay higher prices to the CFC producers for all the CFCs they use.[27] However, transfer payments can be reduced through tax forgiveness or by directly allocating permits to users without requiring payments for the initial allocation. Transfers can also be offset by reimbursements to users. Implementation strategies that mitigate transfer payments in any of these ways result in "compensated" economic incentives policies, which are discussed in Sec. V.

Transfer payments are wealth transfers. This fact is perhaps easiest to recognize for the hypothetical case in which permits are directly allocated to users, who then buy and sell permits among themselves; in this case, the permit revenues are paid by the firms that buy permits and received by the firms that sell permits. The same general principle applies, however, even if the tax or permit payments are paid into the general treasury and later used to help finance government expenditures.

For the firms that pay them, transfer payments are an expense that will be reflected in higher prices to the consumer and a greater risk of plant closures and worker unemployment. Because the transfers are not a real resource cost, the negative effects on firms that pay them will be offset by benefits to the ultimate transfer recipients. Nevertheless, transfers are a policy concern because wealth redistribution and its effects on certain consumer prices and on plant closures are politically sensitive issues.

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[27] Transfer payments are *not* eliminated by setting CFC quotas without using permits. In that case, the CFC producers would have to allocate available supplies in some fashion, probably by raising CFC prices and thereby making themselves the recipients of the transfers. (See Sec. V.)

Under an uncompensated economic incentives policy, cumulative transfer payments would be very large, ranging upward from $1.5 billion for the least costly benchmark-equivalent policy. For the firms that pay them, uncompensated transfers dwarf the costs of reducing emissions. On average, a firm's expenses for transfers under an uncompensated benchmark-equivalent policy are about fifteen times the costs of actually reducing emissions. For all but a few CFC-using firms, the total expenses under uncompensated economic incentives are greater than the compliance costs under mandatory controls.

### Other Dimensions of Policy Comparison

Neither the benchmark mandatory controls nor any of the economic incentive policy scenarios is expected to result in the elimination of any of the consumer products under consideration.[28] Moreover, neither mandatory controls nor a compensated benchmark-equivalent incentives policy (i.e., one designed to mitigate transfer payments) is expected to lead to increases in consumer prices of more than five percent in CFC-using industries. Plant closures and worker unemployment should be rare, with the possible exception of firms that produce rigid packaging foams, where paper and cardboard are highly competitive products. The risk of these detrimental side effects of regulation is greater under uncompensated economic incentives policies, but with offsetting effects elsewhere in the economy.

Although even mandatory controls will encourage some firms to use chemical substitution to avoid costly compliance with CFC regulations, the degree of chemical substitution should be far greater under economic incentives than under mandatory controls. To the extent that the substituted chemicals are found to be hazardous to worker health or the environment, this greater substitution is a disadvantage of economic incentives policies.

Notably, neither mandatory controls nor economic incentives would decrease the use of rigid foam insulation, one major area where restrictions on CFC use would extract a large energy penalty. There are several product areas where incentives to reduce CFC use could cause some increase in energy use, but in no case does it appear that an incentives policy would generate energy penalties nearly as great as those imposed by CFC bans.

Economic incentives offer an important advantage over mandatory controls because there are only five producers of CFCs who would have to be monitored to assure that taxes are collected or the quota is observed. In contrast, enforcement of mandatory controls would require identifying the several thousand CFC users and their plant locations, then monitoring them on an ongoing basis.

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[28] This comment applies even in the case of the rigid packaging foams. Although CFC packaging foams might become less widely used as a result of regulation, the fact that paper and cardboard are close competitors implies that consumers find the competitive products acceptable in several applications.

Economic incentives are more flexible policy tools than mandatory controls. They permit a wider range of emissions reductions, and a given cumulative reduction can be achieved using a variety of timetables for annual tax or quota adjustments. Indeed, if the nature of the ozone depletion problem were deemed so uncertain that a strenuous emissions-reduction program does not yet seem warranted, a permit policy based on a quota only slightly below current CFC use levels could be implemented with low initial costs to industry, and the option of rapidly implementing a more stringent quota at a future date could be retained. In the meantime, very low-cost emissions avoidance would be encouraged, industry would gain familiarity with the policy mechanism, and the regulatory agency could look more deeply into compensation techniques that could be introduced if the policy became more stringent in the future.

Because Congressional authority is required for taxation policy to be changed or implemented, taxes are a somewhat less flexible economic incentives technique than marketable permits might be. At the same time, industry's greater familiarity with taxes and the assurance that each firm could buy as much CFC as it needs, as long as the tax is paid, might lead to greater industry acceptance of the tax approach.

## Policy Options in Perspective

The data in Table 1.6 help put the U.S. policy options in a broader perspective. Over the next decade, in the absence of regulatory action both at home and abroad, the United States will contribute a little over one-fifth to worldwide cumulative CFC emissions. The benchmark mandatory controls, or equally effective economic incentive policies, would reduce total worldwide emissions by about three percent.

Table 1.6 also indicates that even an immediate and total ban on CFC use would reduce U.S. emissions by only about 85 percent, because of the continuing emissions

Table 1.6

CUMULATIVE EMISSIONS OUTCOMES, 1980-1990[a]

| U.S. Outcomes | Cumulative Emissions (billions of permit pounds) |
|---|---|
| Baseline | 5.4 |
| Benchmark | 4.5 |
| Zero growth | 3.6 |
| Ban in 1980 | 0.8 |
| Rest of the world (approximate) | 23.2 |

[a] Calculations performed by Rand. The rest-of-the-world estimate is based on EPA-supplied estimates for CFC-11, CFC-12, and CFC-113.

from the existing CFC bank. Delay in taking action to limit emissions implies further growth in the bank, and a resulting increase in future emissions that would be extremely costly to eliminate.

## RELATIONSHIPS BETWEEN TARGETS AND STRATEGIES

Because this study does not examine the health, environmental, or economic benefits of ozone protection, we have not directly addressed the crucial issue of setting emissions-reduction targets. However, the study does show that the choice of a policy strategy is not independent of the policy target.

Either mandatory controls or economic incentives can achieve modest emissions reductions by 1990. However, given current technology, it does not appear feasible to use mandatory controls to reduce cumulative U.S. emissions by more than 30 percent over the next decade; to do much better than this with mandatory controls would require not only near-term technological innovation, but innovation that is effective without time-consuming capital formation or turnover of the stock of products in use. Short of such fortuitous technological development, an attempt to achieve a more stringent target over the next decade requires a policy choice between economic incentives and CFC bans.

Although CFC bans were not analyzed quantitatively in this study, we are confident that bans would be more costly to the economy as a whole than economic incentives, because incentives do not eliminate CFC applications until all less costly options have been exploited. The costs of the two policy alternatives would be similar only in the extreme case of a virtual elimination of all CFC use. The principal disadvantage of using economic incentives to achieve stringent emissions targets lies in the very large transfer payments that would be generated unless the policy includes compensation. Consequently, if large emissions reductions are the goal, design of a compensated implementation plan for economic incentives would presumably be a major policy concern.

## STRUCTURE OF THE REPORT

Section II explains important features of our methods of analysis. Sections III and III.A through III.H detail the individual product area analyses, including estimates of the effects of mandatory controls and simulations of the product area CFC demand schedules; these sections may be used simply for reference purposes by readers whose primary interest is in the overall comparisons of policy alternatives.[29] Section IV estimates the compliance costs for economic incentive policies that would achieve emissions reductions similar to or greater than those called for by the mandatory controls, and compares incentive policy compliance costs with those of the benchmark controls. Section V discusses a number of implementation issues for economic incentive policies, with particular emphasis on the payments firms might make for the right to use CFCs and how these payments might be reduced or rebated. Section VI presents an overview of the comparisons among policy options.

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[29] Section III establishes important assumptions and terminology common to all the product area analyses and should be read in conjunction with them.

# II. METHODS OF ANALYSIS

The goal of this study is to predict future economic behavior under regulatory and economic conditions that represent radical departures from previous industry experience. Some of the technologies that firms might use to reduce emissions are not yet in widespread use, so their costs and effectiveness are uncertain. Moreover, under economic incentive policies, firms might need to adapt to changes in CFC prices that are several times greater than any experienced by the industry in recent history.

Historical patterns of behavior can provide only limited guidance in predicting the future industry outcomes when economic conditions are drastically altered. Consequently, this study makes predictions by modeling the decisionmaking processes of firms and their customers, then uses the models to simulate quantitative decision outcomes. This section addresses a number of important analytical issues that arose when the models for this research were devised, and describes how the issues have been resolved. The methods and assumptions deserve close scrutiny because they influence the outcome of analyses presented in later sections.

## FINAL PRODUCT DEMAND ASSUMPTIONS

Each of the product areas examined in this study represents a grouping of firms that use CFCs in similar ways and for similar purposes, though not necessarily to produce a single, homogeneous final product. For example, flexible foams consist of slabstock (cut-to-fit) and molded foams of widely varying resiliency and softness, and the foams are used to produce such diverse consumer products as bedding, furniture cushioning, textiles, and carpet underlay. In some of the product areas, the information on the final products produced using CFCs is far from complete. In particular, the only available information concerning the final products produced with CFC solvents is that much of the use is in the electronics industry.

Early in the research it became clear that neither data availability nor research resources would permit empirical demand estimation for the numerous final products under consideration. However, preliminary results of the investigation suggested that it would be appropriate to assume that the final product demand functions are perfectly inelastic (unresponsive to final product prices) within the range of final product price adjustments that could be expected to result from the policies under review.

In every major product area studied here, the use of CFCs is a very minor source of overall final output production costs. For example, even complete passthrough to final consumers of all costs imposed by the benchmark mandatory controls would increase final product prices by less (in most cases, much less) than five percent.[1] When price changes are this small, a perfectly inelastic demand curve yields a good approximation to outcomes for any case in which actual demand is not extremely responsive to price changes.[2]

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[1] Depending on how they are implemented, economic incentives policies could lead to greater product price increases than under mandatory controls. This possibility is discussed later in this section in the context of transfer payments.

Highly elastic (price-responsive) final product demand is a property most commonly encountered for products that have close substitutes whose prices move independently of those of the product in question. For example, imported goods could offer an alternative to domestic products. In most CFC-using product areas, transportation costs limit the domestic market for foreign products enough that the relatively minor domestic price increases anticipated in this research would not lead to large-scale import substitution. But even for those products whose transport costs are not a barrier to imports, the problem of import substitution can be solved by setting tariffs or other import restrictions; this issue is addressed in Sec. V.

Foreign markets for domestically produced goods might have relatively elastic final product demand because of competition from foreign-made goods. The only product we have examined where foreign markets are currently an important source of demand is chillers. This product is also one for which the effect of regulation on final product prices is expected to be so small that it would be easily overlooked by foreign consumers who already encounter far greater price variations for U.S. products due to changes in exchange rates.

There are some applications in some product areas (e.g., flexible foams and solvents) where virtually identical products can be made without CFCs. In these situations, we recognize that there is considerable elasticity of demand for the output of firms that use CFCs, while maintaining the assumption that overall final product demand (which is close to being indifferent about whether the product is made with CFCs) is perfectly inelastic.

While we do not believe that the inelasticity assumption is grossly inaccurate for any product, it is possible that actual final product demand functions have some elasticity in the price range under consideration. Given uncertainty about final product demand, assuming it is perfectly inelastic is, in most respects pertinent to this study, "cautious." To the extent that the assumption is inaccurate, it leads us to underestimate the reductions in CFC use and emissions that would occur after regulatory action. If inaccurate, the assumption would lead us to overestimate the increase in consumer prices due to policy action, and to overestimate the marketable permit price or tax consistent with a particular emissions-reduction goal. In short, perfectly inelastic final product demand is a "worst case" assumption for predicting the economic implications of emissions control, though one we do not expect to be very far from reality.

## CFC DEMAND SIMULATIONS

Given perfectly inelastic final product demand, changes in the cost of producing final products do not affect their output level for the product market as a whole. As a rule, however, competition among firms to maintain or increase their market shares induces them to seek the least-cost method of production. If the cause of increased production costs is an increase in CFC prices, firms will seek to economize on CFC use if the methods available for doing so lead to overall cost savings. The analysis of CFC demand for each product area proceeds by simulating the firm's decisions concerning how best to economize on CFC use.

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[2] The First Fundamental Law of Demand, as specified by Alchian and Allen (1972, p. 60) is: "Whatever the quantity of any good consumed at a particular price, a sufficiently higher price will induce any person to consume less." The argument presented above is that the price changes under consideration here are not sufficiently great to induce significantly lower consumption.

All of the product area simulations assume that the prices of alternative chemicals or for emissions-reducing capital equipment would be unaffected by the increased demand for those products when CFC prices rise. Compared with their non-CFC chemical substitutes, such as methylene chloride or methyl chloroform, CFCs are specialty chemicals with relatively small markets. Even if all CFC use were replaced with alternative chemicals in the flexible foams and solvents product areas, the increase in the markets for the alternative chemicals would be only a few percentage points; it is reasonable to presume, therefore, that the market prices of the alternative chemicals would not be affected by the increased demand for them generated by the CFC policies under consideration here. Similarly, solvent-using equipment and recovery equipment have a much larger market than that generated by CFC use, and so equipment prices should not be affected (except perhaps as a temporary phenomenon) by increased demand for equipment due to CFC regulatory policy.

For the product areas most responsible for CFC emissions, available information permits plausible simulation analyses. For flexible foams and solvents, the simulations indicate that there is substantial elasticity of demand for CFCs. In contrast, for much of the CFC use in rigid foams—for insulation in particular—the simulations imply very low elasticity of CFC demand. The analysis of chillers and retail food store refrigeration also indicates fairly high elasticity but with relatively small effects on CFC use and emissions because current use and emissions are relatively small for these products.

There are some product areas for which available data do not provide a sufficient basis for carrying out the simulations. Automotive air conditioning is the one major source of use and emissions where this is true, but the same difficulty arises for home appliances, and for liquid fast freezing and sterilants and other "miscellaneous" products. To conduct the analysis of the effects of economic incentive policies, we assume that the CFC demand functions in these product areas are perfectly inelastic. However, we provide information indicating that these CFC demand schedules are surely somewhat elastic; we offer some calculation of how much CFC use and emissions might be reduced through economic incentives, though at an unknown price; and we indicate how the results of the analysis of the economic incentive policies would be affected if a plausible degree of CFC demand elasticity were encountered in these product areas at CFC prices within the range under consideration.

## FIRMS' INVESTMENT DECISIONS

If faced by higher prices for CFCs, firms in several of the industries examined in this study have one or more options for reducing CFC use while maintaining current levels of final output production. In most cases, the options require making an initial investment (e.g., for equipment with lower emissions rates) that yields returns for several years thereafter in the form of reduced purchases of CFCs.[3] Our methodology for simulating CFC demand in these industries proceeds by calculating the CFC price at which the present value of net returns over the life of the investment is sufficient to compensate for the initial investment cost. For example, in a simple case where the annual reduction in CFC use is constant over the life of the investment and the investment does not affect operating costs, the formula for the CFC price at which the investment would become profitable is:

$$P^* = rK/\Delta C[1 - \left(\frac{1}{(1+r)}\right)^T ] \text{ ,} \tag{2.1}$$

where K is the initial investment cost, ΔC is the reduction in annual CFC expenditures, r is the firm's opportunity cost of capital, T is the life of the investment, and $P^*$ is the critical value of the CFC price.

In practice, information on the firm's opportunity cost of capital (r) is rarely available. In some cases, even the investment lifetime (T) is uncertain because the functional life of a piece of capital equipment is not necessarily equal to its economic lifespan, especially in industries with rapid rates of technological change or high rates of entry and exit. Finally, information on operating costs, especially fuel requirements, for various types of capital equipment is often unavailable, usually because the equipment is not yet in general use in the industry. In short, the quantitative analysis of investment decisions requires us to make plausible assumptions about the variables in the present value calculations.

Given information only on the initial investment cost (K) and the reduction in annual CFC use (ΔC), there is an unknown factor, F, which would account for the values of r and T such that Eq. (2.1) can be written:[4]

$$K = FP^*\Delta C \tag{2.2}$$

The value of F, which must be assumed, is "robust" in the sense that there are many values of its component variables that would yield the same value of F. For example, if there are no operating cost adjustments, setting F equal to 4 is approximately equivalent to using $r = 0.2$ and $T = 9$, or $r = 0.18$ and $T = 8$, or $r = 0.16$ and $T = 7$. Given some uncertainty about which particular values of r and T are appropriate, it is analytically convenient to rely on an assumed value of F to which several plausible combinations of r and T are equivalent.

It is readily apparent from Eq. (2.2) that F can also be interpreted as the number of years required for the undiscounted cumulative returns on the investment to equal the initial outlay, a concept familiar to industry as the "payback period."[5] We expect this term to be familiar to many of the firms who participated in this study because many firms actually use the simple payback concept[6] rather than internal rates of return or net present value calculations in making their investment decisions. Consequently, the value of F is frequently described as the payback period in the product area analyses, with notes to the text to indicate illustrative values of r and T that correspond to the stated value of F.[7]

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[3] This type of investment is characterized as "point-input, stream-output." As a simplification, the analysis presumes discrete annual returns rather than a continuous stream of returns.

[4] In more complicated formulations of Eq. (2.1), the value of F would include factors reflecting other unknown variables, such as operating cost adjustments.

[5] Gordon (1962) has interpreted the payback period as an indirect though quick measure of investment return. Smith (1961) offers a rigorous analysis showing the conditions under which Gordon's conclusion is correct; the investment conditions appearing in this study meet Smith's requirements. Lutz and Lutz (1951) have even shown that under conditions like those encountered here, maximization of the rate of return is equivalent to minimizing payback.

## A DEFINITION OF TERMS: COMPLIANCE COSTS, RENTS, AND TRANSFER PAYMENTS

Compliance costs, rents, and transfer payments are three components of the cost of regulatory action that are distinguished throughout this study.

### Compliance Costs

Compliance costs refer to the resource costs incurred by firms in adapting to regulation, either by implementing mandated controls or in responding to increased CFC prices. The costs include incremental investment in capital and any net increases in operating (variable) costs. If firms that are not presently using CFCs would begin to use them in the absence of regulation, the cost of forgoing this opportunity is included in the estimates. If firms find it less costly to substitute an alternative chemical for CFCs than to implement, say, mandatory recovery and recycle of CFCs, the cost of conversion to the alternative chemical, rather than the cost of implementing mandatory controls, is measured in the compliance cost estimate.

### Rents

Under perfectly inelastic final product demand, all compliance costs are passed through to final consumers in the form of higher product prices. In the short run, some CFC users in a product area may have higher compliance costs than others. For example, the net cost of compliance with mandatory recovery and recycle would be higher for small firms (which have less CFC to recover) if the required investment in recovery equipment does not vary with the size of the firm. If final product prices rise enough to cover the costs of the highest compliance-cost firms, firms with lower compliance costs will receive higher prices than needed to compensate them for their own production costs. In time, market adjustment (perhaps through entry and exit of firms) tends to eliminate major cost differentials among competing firms, but in the short run (a period of uncertain length) some firms in the industry will earn "rents"—revenues in excess of production costs and normal profits. Because the value of rents is exceedingly difficult to predict and because they are temporary, we do not measure rents as part of the cost consumers would pay for regulation. However, the prospect that there will be some rents in some product areas for some period of time deserves recognition in that it implies that consumer prices might initially rise more than the analysis predicts under the assumption that only compliance costs are passed through by firms.

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[6] A 1971 survey (Fremgen, 1972) of 177 business firms in a variety of industries showed that 67 percent use the payback period as a criterion for evaluating investments, though often in combination with other, more complex criteria.

[7] In some instances, when we suspect that the economic life of equipment is shorter than its functional life, we describe T as the period required for payback, but we also cite an assumed "discount rate" for the value of r. This is equivalent to using a modified payback rule.

## Transfer Payments

The third component of the costs of regulation, transfer payments, exists only under economic incentives policies. If a CFC tax is levied, the tax payments by firms are transfer payments; they enter the general treasury, from which the payments are ultimately used to help finance government purchases of goods and services. If regulation imposes a quota on CFC sales and the government sells permits for CFC use, the payments for permits are transfers that also would enter the general treasury and ultimately return to the economy elsewhere. If the permits are given to the CFC producers who then sell them to users, the producers receive the transfers. Even if the permits are directly allocated to the CFC users free of charge, any sales among users in the permit aftermarket still result in transfers, in this case from the buyers of permits to the sellers; however, to the extent that direct allocation to users reduces the number of permits that are bought and sold, the total magnitude of transfer payments is reduced.

Finally, if a quota is set for CFC sales but no permits are issued, and if the CFC producers allocate the restricted CFC supplies among users by raising the prices of CFCs—which is not unlikely—then the increase in CFC prices generates transfers from the CFC users to the producers, just as in the case of direct allocation of permits to the producers. Although a regulatory policy that sets quotas without permits is not a focus of attention in this study, the implications of such a regulatory strategy are discussed in Sec. V.

More generally, the magnitude and distribution of transfer payments depend on how an economic incentives policy is implemented. Transfers are at a maximum if all users must pay taxes, buy permits, or otherwise pay increased prices for all the CFCs they use; policies with this result are described here and elsewhere in this report as "uncompensated." Policies that reduce transfer payments (or reimburse firms for the payments) are described as "compensated" incentives policies. Various compensation approaches, including direct allocation, are discussed in Sec. V of this report.

Unlike compliance costs, transfer payments do not result from an increased use of real resources in CFC-using industries, and thus do not restrict the ability of the rest of the economy to produce goods and services. The transfers do raise the costs of doing business for the firms that pay them, leading to increased consumer prices and greater risks of plant closures and worker unemployment for those firms. However, the transfers ultimately reenter the economy elsewhere, with offsetting effects on prices, investment, and employment in other industries.[8] Consequently, transfer payments are properly excluded when the focus of analysis is on the effects of policy on the economy as a whole, as in Sec. IV of this report.

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[8] Transfer payments can cause short-run economic dislocations, both because the transfers might not reenter the economy instantaneously and because some human and physical capital is firm- or industry-specific and fixed in the short run. Like the short-run phenomenon of rents, temporary dislocations due to transfer payments are omitted from the quantitative analysis of policy effects in this study.

The effects of alternative policies on the economy as a whole represent, however, only one dimension of policy comparison in this study. Another is the extent to which various policies result in a redistribution of wealth among firms, industries, and consumers. Wealth redistribution is relevant because it is politically sensitive. Even when alternative policies yield the same benefits in terms of emissions reduction, neither firms nor policymakers are indifferent to the distribution of the costs of the regulation—especially if some distributions of costs could lead to plant closures, worker unemployment, or high consumer prices in certain industries.

All regulations impose costs that vary from one firm or industry to another; the benchmark mandatory controls, for example, would impose costs only on those CFC-using firms for which controls are implemented and enforced, leaving many users unaffected. Thus, compliance costs alone imply some redistribution of wealth. Because transfer payments also redistribute wealth, they are included in the analysis of the distributive effects of incentive policies. The transfers prove to be especially important in the analysis, both because the payments would be many times larger than compliance costs under an uncompensated incentives policy and because the size of the transfers can be reduced through compensation techniques.

## PLANT CLOSURE PROGNOSIS

Over the next decade, some production and sales facilities in the United States will be shut down. Some of the closures will occur in the product areas examined in this study. In a few cases, primarily those where the economic survival of the firm is already borderline, CFC regulation could contribute to the closure and it would be difficult (if not impossible) to determine with certainty whether regulation is the critical factor. As a general rule, however, we do not expect the benchmark mandatory controls to cause plant closures in most of the product areas examined here. The few possible exceptions to this rule are noted here and discussed in more detail in Secs. III.A through III.H.

In principle, even regulations that fall far short of banning a product can cause the shutdown of some production facilities in an industry. There are two ways this can occur: The regulations can cause product prices to rise enough to reduce final product demand, or they can cause an increase in the optimal scale of production,[9] leading some plants to expand output enough to displace their smaller competitors.

Since the final product demand functions for the products examined here appear to be extremely inelastic within the relevant price ranges, plant closures for the first of the reasons listed above should be rare, and those that do occur would result from highly localized demand conditions. The possible exceptions to this general rule occur in situations where there are substitute final products that do not use CFCs *and* the substitute products cannot be made with the same capital equipment that is used in CFC-based production.[10] The principal cases where substitution requires a different capital stock are packaging applications of rigid nonurethane foams (where paper and cardboard are among the substitutes), in liquid fast freezing (where cryogenic and mechanical freezing are alternatives), and possibly in sterilants (where the alternative use of pure ethylene oxide or ethylene oxide-carbon dioxide blends may be feasible). Of these product areas, only rigid packaging foams would be subject to regulation under the benchmark mandatory controls. The likelihood of plant closures in this product area is discussed in Sec. III.C.

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[9] Intuitively, the optimal scale of production is the output level of a firm that produces at the lowest possible production costs per unit of output and is thus able to charge its customers low prices while continuing to earn a reasonable profit. Regulations can change production costs so that the least costly method of production occurs at a higher output level per firm, i.e., the optimal scale of production increases.

Increases in the optimal scale of production depend on whether a policy raises fixed costs of production.[11] Mandatory controls that raise fixed costs, and hence tend to increase the optimal scale of production, are recovery and recycle of CFC losses and equipment improvements to reduce CFC loss rates. Controls that increase only variable costs are those that require or induce substitution of an alternative chemical for the CFCs (provided no capital investment is required to make the transition).

Given inelastic final product demand, changes in optimal scale are necessary but not sufficient for there to be substantial numbers of plant closures. If final product demand is growing fairly rapidly, firms can "afford" to operate for a time at less than optimal scale. In time, existing plants will be able to increase their scale of production to optimal levels without displacing other firms already in the market. There will simply be fewer new entrants to the market than there would have been in the absence of regulation. This is the outcome we find most plausible for flexible foams and rigid nonurethane packaging foams. For the remaining product areas, the anticipated changes in optimal scale appear too small relative to current scale to result in plant closures, especially given the observation that there is already considerable variation in scale of operation among existing plants.

All of the preceding comments on the likelihood of plant closures apply equally well to outcomes under compensated economic incentives policies, because the costs of regulation to the CFC-using industries would be lower than under the mandatory controls. However, uncompensated policies would generate transfer payments many times as high as compliance costs, and CFC-using firms would face total regulatory costs much higher under such policies than under mandatory controls. Consequently, there is greater risk of plant closures under uncompensated economic incentives policies.

## PROGNOSIS FOR INFLATION

Economists distinguish between inflation, a rise in the general level of prices, and changes in relative prices. Inflation occurs when the money supply expands relative to the supply of goods and services, or when the supply of goods and services contracts relative to the money supply. Because environmental quality does not appear explicitly in measures of the output of goods and services, an increased use of resources in producing or protecting environmental quality appears as an inflationary reduction in economic output. Consequently, the compliance costs generated by CFC regulation are inflationary. However, the inflationary impact of the CFC regulations studied here would be quite modest, raising consumer prices by less than five percent due to compliance costs in CFC-using industries, and having little if any effect on prices elsewhere in the economy.[12] We expect such effects to be imperceptible.

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[10] Although there are substitutes for CFCs in flexible foams and solvents, the substitutes can be used with the existing capital stock and so plant closures would not be caused by the elasticity of demand for the CFC-made products.

[11] If a regulation increases only variable costs, the firm's average cost curve rises vertically, leaving the output level of minimum average costs unchanged. Increased fixed costs shift the average cost curve to the right as well as upward, increasing the level of output at which average costs are minimized. Reductions in variable costs can offset this effect, but the offset is not sufficient in the cases considered here because a necessary outcome of regulation is an increase in total costs.

Transfer payments under uncompensated economic incentives policies would cause larger final product price effects in the CFC-using industries, but would be largely offset by price reductions elsewhere in the economy. Consequently, transfer payments cause changes in relative prices but do not contribute to inflation according to the economic definition of this term.

## THE ARGUMENT AGAINST NEW SOURCE STANDARDS

In contemplating mandatory controls that set standards for production processes, a regulatory agency has the option of applying the control only for new firms and equipment purchases ("new source standards") or also requiring that existing firms bring their production processes up to the standard (described herein as "retrofit controls"). For some CFC applications, there are also the options of requiring redesign of newly produced products and replacement of the stock of final products in use; these options are pertinent for rigid insulating foams and for refrigeration products, all of which emit CFCs during normal use and at product disposal. Though all options are discussed, only retrofit controls on production processes are included in the set of benchmark mandatory controls.

The options involving redesign of newly produced products to reduce their emissions during normal use of the product or at disposal are not included in the benchmark because most of the emissions effects would occur after 1990, the horizon of the quantitative analysis in this study. Before they could generate their full potential in emissions effects, these options would require further research and development, followed by retooling of the industry, and then followed by a period of time to allow for turnover in the existing stock of the products. Most of the costs of implementing the options would occur at the beginning of this adjustment process, and thus would appear in the cost data for the period 1980 through 1990. To include these options in the benchmark controls would result in an unfavorable comparison of controls with incentives over the first decade of the policy. Therefore, the options have been omitted from the benchmark controls. However, the product area analyses do examine the costs and longer-range emissions effects of the options that have potentially sizable long-range emissions effects.

The options of replacing the stock of various CFC-containing products currently in use are not considered here. Some of these options would be extremely costly and difficult to enforce, such as replacement of rigid insulating foams already in structures. For automotive air conditioners, systems that might currently be used to replace existing units would have relatively small effects on emissions compared to new systems that might be developed in the future, suggesting that it might be worthwhile to defer a replacement strategy, at least until there has been further technical assessment of systems that are still on the drawing boards. For insulating foams, the replacement materials that are currently available would severely increase energy utilization, as indicated by analysis presented in Sec. III.C. For the remaining products (home refrigerators and freezers, chillers, and retail food store refrigeration systems), the emissions benefits of replacement are small relative to other and far less costly CFC policy actions.

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[12] Prices elsewhere in the economy would be affected only to the extent that the supply of factor inputs is less than perfectly elastic and the increased use of factors in CFC-using industries causes upward movement along the supply curve.

New source standards on production processes (e.g., equipment standards and recycling requirements) would effectively reduce emissions by 1990 (the horizon for this analysis) only if: (a) in the absence of controls, new sources established between now and 1990 would account for a significant fraction of CFC use and emissions over the period; (b) in the absence of the controls, the new sources would not meet the standards; and (c) the standards themselves do not encourage the prolonged or more intensive use of existing equipment and operating practices that fall short of meeting the standards. One or another of these conditions is violated in nearly all of the product areas examined here.

In all the refrigeration product areas, we anticipate that existing firms and capital equipment will be sufficient to satisfy final product demand for several years to come. Consequently, new production facilities for these products would account for only a small share of CFC use by 1990.[13] The simulation analysis for solvents suggests that much of the new equipment purchased between now and 1990 would meet proposed emissions control standards even in the absence of policy action, so new source standards would have only a small incremental effect in reducing emissions.

Flexible foam production facilities are expected to increase in number between now and 1990 in the absence of regulatory action. However, there appears to be considerable opportunity for increasing production from existing plants. Where output from existing plants can be increased, new source standards encourage such expansion and discourage new plant construction by increasing production costs for new plants relative to older ones, thereby putting new plants at a competitive disadvantage.[14] Since output expansion appears feasible for older flexible foam plants, new source standards would probably not greatly reduce emissions by 1990 in this product area. A similar situation arises with respect to certain rigid packaging foams, as explained in Sec. III.C.

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[13] Even if new production plants were to be built before 1990 in the absence of controls, controls would probably delay capital expansion in these markets for the same reason given below concerning flexible foams.

[14] New source standards cause the average cost curves of new plants to lie above those for older plants. Consequently, older plants can profitably increase production beyond the minimum point on their average cost curves.

## CUMULATIVE EMISSIONS AS A BASIS FOR POLICY COMPARISON

According to information supplied by the EPA, models of atmospheric chemistry indicate that the ultimate effect on the ozone layer is essentially the same for a given cumulative emissions level, regardless of whether the emissions occur in a brief burst or over a period as long as a decade. The time profile of emissions does affect the future date at which the ultimate ozone effect occurs. In principle, therefore, the emissions effects of alternative policies should be adjusted (discounted) to reflect differences in the timing of ozone depletion outcomes. However, given that the ultimate ozone effect would be reached only after several decades in any case, discounting would not perceptibly alter the measured differences among the effectiveness of alternative policies.[15] Consequently, our analysis compares the outcomes of alternative policies on the basis of their undiscounted cumulative emissions effects between 1980 and 1990.

Different policy strategies can lead to different time profiles of emissions even if cumulative emissions effects are equal. Mandatory controls "bite" as soon as they are implemented, causing an immediate reduction in emissions relative to the baseline level. Thereafter, emissions levels grow commensurately with growth in user industries. In contrast, with economic incentives policies it is possible to select alternative time profiles of emissions that produce a given cumulative reduction.

A policy involving a constant tax or marketable permit price yields a time profile most similar to that of mandatory controls. Allowing taxes or marketable permit prices to rise over time yields an emissions profile that does not show as large a decline in early years but compensates with greater declines in later years. While tax rates tend to be inflexible over time because they usually can be changed only through legislative action, it does not appear as difficult operationally to vary a CFC annual quota such that marketable permit prices would vary. The latter feature offers a degree of flexibility in marketable permit prices that can be used to some advantage, both in allowing industry some time to become familiar with the new policy mechanism and also in helping to reduce cumulative compliance costs. The latter point is illustrated in Sec. IV.

## DISCOUNTED CUMULATIVE COSTS AS A BASIS FOR POLICY COMPARISON

In contrast with the measures of cumulative emissions reductions, all measures of cumulative costs are discounted in this study. Policies can differ considerably in the time profile of compliance costs and transfer payments imposed on industry, and discounting accounts for the fact that firms are not indifferent to when regulatory expenses are incurred.

Suppose, for example, that a firm can invest its money in profitable enterprise to earn a return of 11 percent per year, and that one policy option would require the firm to spend $1,000 in regulatory expenses in 1980. If there were an alternative policy that would allow the firm to put off its regulatory expenses until 1985, the firm could earn $685 by investing $1,000 elsewhere for five years. Other things equal, the firm would be indifferent between an alternative policy requiring an expense of $1,685 in 1985 and the original policy requiring an expense of just $1,000 in 1980. Using a discount rate of 11 percent, our estimate of the cumulative costs of these two (hypothetical) policy alternatives would be equal.

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[15] This is especially true for comparisons of effectiveness between mandatory controls and the benchmark-equivalent, constant-price economic incentives policy because the time patterns of emissions are similar under the two policies.

Throughout this study, we use a discount rate of 11 percent per year to discount future regulatory expenses.[16] This discount rate is specified in real terms; it implies that a firm could earn a (money) rate of return of 24 percent in years when the inflation rate is 13 percent, as it was in 1979. The specific value of 11 percent was chosen for consistency with cost-benefit analyses of the ozone-depletion problem being performed by Dr. Martin Bailey at the University of Maryland and by Dr. Daniel Dick and others at the Stanford Research Institute. Dr. Bailey reasons that 11 percent is the proper rate to use because it is the current real yield on nonconstruction investment in the United States.

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[16] Higher rates are used to analyze investment decisions for individual product areas in part to offset incomplete data on investment costs and in part to reflect the unusual uncertainty surrounding investments required or induced by regulatory action.

# III. INTRODUCTION TO THE PRODUCT AREA ANALYSES

The results of detailed analyses of major categories of products made using CFCs are summarized under each of several topic headings to follow.[1] The topic headings are:

A. Flexible Urethane Foams
B. Solvents
C. Rigid Urethane and Nonurethane Foams[2]
D. Mobile Air Conditioning
E. Chillers
F. Home Refrigerators and Freezers
G. Retail Food Store Refrigeration
H. Miscellaneous

Topic H examines a number of smaller categories of CFC use, including fire extinguishers, liquid fast freezing, sterilants, and dehumidifiers.

The ordering of topics reflects a distinction between two types of emissions processes. Flexible foams and solvents are both categories of use whose emissions are "prompt," by which we mean that virtually all the CFC entering use in a given year is emitted in that same year. The remaining categories of use involve some degree of "banking." A substantial portion of the CFC entering these uses in a given year is stored in the products and emitted in future years. Although some relatively small uses within the rigid foams category are prompt emitters, all the rigid foams are treated together as a matter of expositional convenience.

CFC labeling in the product area summaries follows product area conventions. Hence, when denoting CFCs used in refrigeration categories, we use the "R" prefix (e.g., R-11, R-12). In the nonrefrigeration categories, we revert to the more general designations using the "CFC" prefix.[3] When CFC-22 use and emissions are subtracted from CFC totals, the remainder is described as "non-R-22" or as "fully halogenated CFCs."

## PLACING THE PRODUCT AREAS IN PERSPECTIVE: AN OVERVIEW OF USE AND EMISSIONS

Table 3.1 lists the estimates of 1976 use of each of the major CFCs for each of the product areas analyzed in this report. Also shown is the production of CFCs not accounted for by the analyzed product areas. Overall, the analyzed product areas account for about three-quarters of total CFC production, including R-22. Over 70 percent of the production not accounted for by the analyzed product areas is com-

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[1] For an examination of the industries related to CFC production, see Wolf (1980).

[2] Elsewhere in this report, these foams may be labeled "closed cell" foams.

[3] Some readers may be familiar with the "F" prefix. This prefix refers to "Freon," which is a DuPont trade name. As a courtesy to other producers of CFCs, the prefix is not used here.

## Table 3.1

### ESTIMATED CFC PRODUCTION AND NONAEROSOL END USE, 1976

(Millions of pounds)

| | CFC-11 | CFC-12 | CFC-22 | CFC-113 | Total | Total Minus CFC-22 |
|---|---|---|---|---|---|---|
| Total domestic production: | 256 | 393 | 170 | 72 | 891 | 721 |
| Sales for nonaerosol use: | 99 | 189 | 117 | 69 | 474 | 357 |
| Analyzed applications | | | | | | |
| Flexible foam | 34 | -- | -- | -- | 34 | 34 |
| Solvents | -- | -- | -- | 69 | 69 | 69 |
| Rigid foams | | | | | | |
| Urethane | 35 | 2 | -- | -- | 37 | 37 |
| Nonurethane | 2 | 21 | -- | -- | 23 | 23 |
| Mobile air conditioning | -- | 90 | -- | -- | 90 | 90 |
| Other refrigeration | | | | | | |
| Chillers | 8 | 5 | 3 | -- | 16 | 13 |
| Home refrigerators and freezers | -- | 6 | -- | -- | 6 | 6 |
| Retail food | -- | 11 | 1 | -- | 12 | 11 |
| Miscellaneous | | | | | | |
| Liquid fast freezing | -- | 6 | -- | -- | 6 | 6 |
| Sterilants | -- | 13 | -- | -- | 13 | 13 |
| Others | 1 | 3 | -- | -- | 4 | 4 |
| Total | 80 | 157 | 4 | 69 | 310 | 306 |
| Other applications | | | | | | |
| Home air conditioning | -- | -- | 46 | -- | 46 | -- |
| Supermarket air conditioning | -- | -- | 29 | -- | 29 | -- |
| Other | 19 | 32 | 38 | -- | 89 | 51 |
| Total | 19 | 32 | 113 | 0 | 164 | 51 |

SOURCES: Estimates of total domestic production and sales for nonaerosol use are based on data supplied by the CFC producers. Usage levels in the analyzed applications are based on data developed by Rand and International Research and Technology Corp. (IR&T), as explained elsewhere in this report. Usage levels for other applications are from Dupont (1978a). Total domestic production includes production for aerosol use.

NOTE: Sales for nonaerosol use equal production minus internal use by the CFC producers, exports, and emissions during packaging and transport to users. Imports should be included, but data were not available for most of the CFCs. Uses reported for individual applications exclude: 1 million pounds of CFC-114 used mostly in chillers; 5 million pounds each of CFC-22 and CFC-115 used to form CFC-502 used in retail food refrigeration; and less than 1 million pounds of CFC-12 used to form CFC-500 used in chillers.

posed of R-22 used in home and supermarket air conditioners, product areas outside the scope of this study.

Table 3.2 reports estimated emissions for 1976 by CFC and product area. The emissions estimates are generally similar to the use estimates, even for product categories in which there is banking. For the refrigeration categories, the similarity between use and emissions is largely attributable to a near-steady-state phenomenon; new additions to the stock of refrigerant in home appliances, for example, are roughly offset by losses from unit disposals. In rigid foams, emissions are much smaller than use because the market is youthful and relatively little of the historical addition to the bank has reached the disposal stage.

Tables 3.3 and 3.4 report projected use and emissions for 1990. Total CFC production was projected from data provided by the CFC producers; notably, the producers disagree sharply about expected growth in production. The preceding comments about the similarities between use and emissions in 1976 apply to the data for 1990 as well.

## THE DATA

In all of the product areas, estimates of "current" CFC use refer to the most recent year for which industry sources were able to provide documentation at the time the data were being collected; in most cases, the current use estimates refer to 1976. Estimates of current and historical emissions derive from current and historical use data and from models of the various product area emissions processes. Although the mandate for this study required developing historical data only from 1970 on, product sales data from years prior to 1970 were sometimes required in order to estimate emissions from the CFC bank.

This study relies heavily on IR&T's analyses of the refrigeration products (mobile air conditioning, chillers, retail food store refrigeration, and home refrigerators and freezers), but some changes have been made. Such deviations from the IR&T documentation are noted where pertinent.

Whereas the CFC producers are the major sources of data on current use of CFCs for each product area, final product producers provided much of the information necessary for projecting future levels of use. An important exception is in solvents, where user industries are diverse and the CFC producers presumably have the best vantage point for assessing overall market trends. In all product categories, the basis for future projections is an analysis of *anticipated* market forces, such as population growth or commercial construction trends. Although past trends in CFC market growth helped inform the projections, simple extrapolation of past trends is not the sole basis of any of the projections, either by Rand or by IR&T.

In several of the product areas, users anticipate changes in CFC use patterns or emissions, such as increased reliance on recovery and recycle or reduced average CFC use per unit of final product. Where such adjustments are already under way or where existing market forces seem to warrant such adjustments in the near future, the projections of CFC use and emissions incorporate the adjustments.

Table 3.2

ESTIMATED CFC NONAEROSOL EMISSIONS FROM ANALYZED END USES, 1976
(Millions of pounds)

| Analyzed Applications | Emissions During 1976 | | | | Combined Non CFC-22 Emissions | | |
|---|---|---|---|---|---|---|---|
| | CFC-11 | CFC-12 | CFC-22 | CFC-113 | Prompt | From the Bank | Total |
| Flexible foam | 34 | -- | -- | -- | 34 | 0 | 34 |
| Solvents | -- | -- | -- | 69 | 69 | 0 | 69 |
| Rigid foams | | | | | | | |
| Urethane | 13 | 1 | -- | -- | 5 | 9 | 14 |
| Nonurethane | 2 | 17 | -- | -- | 19 | (a) | 19 |
| Mobile air conditioning | -- | 76 | -- | -- | 8 | 68 | 76 |
| Other refrigeration | | | | | | | |
| Chillers | 7 | 5 | 3 | -- | (a) | 12 | 12 |
| Home refrigerators and freezers | -- | 5 | -- | -- | (a) | 5 | 5 |
| Retail food | -- | 10 | 1 | -- | 1 | 9 | 10 |
| Miscellaneous | | | | | | | |
| Liquid fast freezing | -- | 6 | -- | -- | 6 | -- | 6 |
| Sterilants | -- | 13 | -- | -- | 13 | -- | 13 |
| Other | 1 | 3 | -- | -- | 4 | -- | 4 |
| Total | | | | | | | |
| Prompt | 41 | 49 | -- | 69 | 159 | -- | 262 |
| From the bank | 16 | 87 | 4 | -- | -- | 103 | |

NOTE: Calculations performed by Rand and explained in the product area analyses elsewhere in this report. Estimates are approximate due to omitting certain CFCs and to rounding. Omitted amounts are: (a) less than a million pounds of CFC-12 used to form CFC-500 for use in chillers; and (b) 3 million pounds each of CFC-22 and CFC-115 used to form CFC-502 for use in retail food store refrigeration. Also, the amount shown for CFC-11 in nonurethane foams includes very small amounts (probably less than a quarter million pounds each) of CFC-113, CFC-114, and CFC-115.

[a] Less than half a million pounds.

## SOURCES OF UNCERTAINTY[4]

Relative to the amount of detailed analysis performed during this research, the summaries presented in this document are brief. Brevity is achieved in part by omitting detailed discussion of the various sources of uncertainty. Consequently, the various product area summaries either present alternative estimates of major variables or note the possible ranges of the variables as indicated by a sensitivity analysis. Beyond this, it is useful in this introduction to consider the several different sources of uncertainty and how they vary in importance among product areas.

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[4] Many of the estimation procedures used here involve chain calculations using many parameters, each containing some degree of rounding error. Redoing the calculations at different degrees of precision can change the estimates by several millions of pounds. We have balanced considerations of underlying data accuracy and research time requirements against the desire for accurate estimation in selecting the levels of precision for the calculations. Overall, the estimates contain rounding errors of less than 10 percent. Rounding error, strictly speaking, is not caused by uncertainty, and thus is not covered in the discussion of sources of uncertainty.

## Table 3.3

### ESTIMATED CFC PRODUCTION AND NONAEROSOL END USE, 1990

(Millions of pounds)

|  | CFC-11 | CFC-12 | CFC-22 | CFC-113 | Total | Total Minus CFC-22 |
|---|---|---|---|---|---|---|
| Total domestic production: | 262 | 363 | 385 | 147 | 1,157 | 772 |
| Sales for nonaerosol use: | 228 | 327 | 265 | 147 | 967 | 702 |
| Analyzed applications |  |  |  |  |  |  |
| Flexible foam | 72 | -- | -- | -- | 72 | 72 |
| Solvents | -- | -- | -- | 147 | 147 | 147 |
| Rigid foams |  |  |  |  |  |  |
| Urethane | 154 | 5 | -- | -- | 159 | 159 |
| Nonurethane | 8 | 59 | -- | -- | 67 | 67 |
| Mobile air conditioning | -- | 125 | -- | -- | 125 | 125 |
| Other refrigeration |  |  |  |  |  |  |
| Chillers | 14 | 6 | 4 | -- | 24 | 20 |
| Home refrigerators and freezers | -- | 9 | -- | -- | 9 | 9 |
| Retail food | -- | 10 | 1 | -- | 11 | 10 |
| Miscellaneous |  |  |  |  |  |  |
| Liquid fast freezing | -- | 15 | -- | -- | 15 | 15 |
| Sterilants | -- | 40 | -- | -- | 40 | 40 |
| Other | 4 | 11 | -- | -- | 15 | 15 |
| Total | 252[a] | 280 | 5 | 147 | 684[a] | 679[a] |
| Other applications | 0 | 47 | 260 | 0[b] | 307 | 47 |

SOURCES: Estimates of total domestic production and sales for nonaerosol use are based on data supplied by the CFC producers. Usage levels in the analyzed applications are based on data developed by Rand and International Research and Technology Corp. as explained elsewhere in this report. Usage levels for other applications are from Dupont (1978a).

NOTE: Sales for nonaerosol use equal production minus internal use by the CFC producers, exports, and emissions during packaging and transport to users. Uses reported for individual applications exclude 2 million pounds of CFC-114 used mostly in chillers; 7 million pounds of CFC-22 and 8 million pounds of CFC-115 used to form CFC-502 for use in retail food store refrigeration; 2 million pounds of CFC-12 used to form CFC-500 for use in chillers.

[a] Our calculations of use in analyzed applications conflict with producer projections of sales available for use.

[b] Refrigeration and other relatively small miscellaneous uses of CFC-113 are included in the solvents data.

Forecasting market trends is inherently uncertain. In the present analyses, baseline trends in final product output are based on industry-supplied market projections or are derived by linking product market trends to trends in major economic and social indicators, such as growth in the number of U.S. households. The indicator variable trends were taken from previously published sources. Over decades or longer periods, related variables do tend to show similar basic trends. There can be, however, considerable independent variation around a general trend, so growth rates predicted for individual years are less certain. Because IR&T

## Table 3.4

### PROJECTED CFC NONAEROSOL EMISSIONS, 1990
(Millions of pounds)

| | | | | | Combined Non CFC-22 Emissions | | |
|---|---|---|---|---|---|---|---|
| Analyzed Applications | CFC-11 | CFC-12 | CFC-22 | CFC-113 | Prompt | From the Bank | Total |
| Flexible foam | 72 | -- | -- | -- | 72 | 0 | 72 |
| Solvents | -- | -- | -- | 147 | 147 | -- | 147 |
| Rigid foams | | | | | | | |
| Urethane | 57 | 2 | -- | -- | 17 | 42 | 59 |
| Nonurethane | 8 | 46 | -- | -- | 52 | 2 | 54 |
| Mobile air conditioning | -- | 122 | -- | -- | 5 | 117 | 122 |
| Other refrigeration | | | | | | | |
| Chillers | 12 | 5 | 4 | -- | (a) | 17 | 17 |
| Home refrigerators and freezers | -- | 7 | -- | -- | (a) | 7 | 7 |
| Retail food | -- | 9 | 1 | -- | 1 | 8 | 9 |
| Miscellaneous | | | | | | | |
| Liquid fast freezing | -- | 15 | -- | -- | 15 | -- | 15 |
| Sterilants | -- | 40 | -- | -- | 40 | -- | 40 |
| Other | 4 | 5 | -- | -- | 8 | 1 | 9 |
| Total | | | | | | | |
| Prompt | 100 | 110 | 0 | 147 | 357 | 0 | 551 |
| From the bank | 53 | 141 | 5 | 0 | 0 | 194 | |

NOTE: Calculations performed by Rand and explained elsewhere in this report. Estimates are approximate due to omission of certain CFCs and rounding errors. Omitted amounts are: (a) 2 million pounds of CFC-114 used in chillers; (b) 1.5 millions pounds of CFC-12 contained in CFC-500 used in chillers; and (c) 6 million pounds of CFC-22 and 7 million pounds of CFC-115 contained in CFC-502 used in retail food store refrigeration. Data for nonurethane foam emissions of CFC-11 may include small amounts of CFC-113, CFC-114, CFC-115.

[a] Less than half a million pounds.

typically did not report projections for individual years between 1976 and 1990, Rand has computed the average annual rates of change implied by the IR&T data.

A particular uncertainty arises in the baseline projections for flexible and rigid urethane foams, both of which emit toxic gases when burned. Given the hazard of accidental fires in homes and workplaces, where these foams are becoming ubiquitous, future regulatory action is a prospect that should not be ignored. These industries are continually improving the flammability properties of the foams, and industry sources uniformly believe this problem will not restrict the growth of urethane foam markets. Nevertheless, if there is such regulation, the baseline projections given here might be overstated.

Given the baseline trends estimated for final product output, CFC purchases in each product area depend on the CFC used per unit of final product and the amount of recovery and recycle of CFC. For flexible foams and solvents, a source of uncertainty about CFC use per unit of final product is the possibility of substituting an alternative chemical for the CFC. The baseline projections for these product areas assume that the CFC share of the final product market will be stable. The major reason for uncertainty about this assumption is that some of the alternative chemicals have been under investigation for regulatory control; if such controls on alternative chemicals are implemented, they could greatly increase the baseline projections given here.

In many product areas, there are techniques for reducing CFC use that would be induced by increases in CFC prices; this fact is essential to the analysis of CFC demand. An uncertainty arises, however, because future trends in CFC prices in the absence of regulation are largely unknown. Because CFCs are made from petroleum-based chemicals,[5] it is reasonable to suppose the prices of CFCs will rise over the next decade. However, prices of potential substitutes for CFCs, many of which are also made using petroleum-based chemicals, are also likely to rise. Similarly, increased petroleum prices will increase the costs of manufacturing generally, raising all costs of production and raising the costs of equipment that might be used to help control CFC emissions. The analysis presented here presumes that the prices of CFCs measured relative to other chemical and equipment prices will remain constant over the period 1980 to 1990. The one exception to this rule is the price of CFC-113 which, from producer supplied data, is expected to fall as CFC-113 production increases; this case is discussed in the section on solvents (Sec. III.B).

For flexible foams, solvents, and nonurethane foams used in packaging, the fact that emissions are prompt means that the annual emissions estimates are as certain as the CFC use estimates on which they are based. In all the product areas where CFCs are banked, however, there is considerable uncertainty about the share of CFC use that is emitted promptly during manufacture and about the rate at which the banked CFC is emitted over time. Moreover, the reported estimates for emissions at final product disposal are extremely uncertain, due to lack of information on how final products are disposed, how much CFC might be retained indefinitely in the disposed product, or how long after disposal the emissions might occur.

Because we have repeatedly sought industry comment on the data, we anticipate few disputes over the baseline projections of CFC use and emissions.[6] However, we do anticipate considerable industry criticism of the estimates of industry and consumer responses to changes in CFC prices. It is common in debates over regulatory policy for industry to argue that demand is not responsive to price. Indeed, a basic belief in the responsiveness of firms and individuals to price incentives seems rare outside the economics profession. To be sure, price responsiveness might be limited indeed. Where our analysis does presume some price responsiveness, we have carefully documented our reasoning. More generally, our analyses are cautious in their presumptions about both CFC user and final product consumer price response, so that the uncertainty largely concerns how much we have *underestimated* the degree to which price increases for CFCs would motivate actions to reduce emissions and *overestimated* the welfare losses associated with emissions reductions. (See Sec. II.)

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[5] CFCs are produced from several petrochemicals, including methane, propylene, and ethylene.

[6] An exception might be normal use emissions from rigid urethane foams. (See Sec. III.C.)

Where price responsiveness would require that firms make capital investments to reduce CFC use, we believe our assumptions are also cautious. While we believe most industry sources have been sincere in attempting to project investment costs accurately, we also recognize that there may be a tendency for firms to overestimate the costs, both to account for the riskiness of investment and to emphasize the potential severity of the short-run economic dislocation that mandatory requirements to invest might impose. The decision-to-invest models were discussed in more detail in the preceding section of this report.

Some readers, particularly those with detailed knowledge of the technologies involved in CFC use, will observe that some promising new technological opportunities for emissions control are omitted from this analysis. New product designs, new production processes, and new chemicals—particularly new CFCs with properties that should make them less hazardous to the ozone layer—are currently being sought by researchers at the major chemical companies and also at some of the larger CFC-using firms. Although the details of recent discoveries are proprietary and carefully guarded, there is evidence that some new options have passed the stage of conceptual development and are being tested for operational feasibility. A few such options are mentioned here in the product area analyses, but others are omitted altogether.

Until a technology is actually used to produce goods for sale in a market, there are substantial uncertainties about the operational advantages or disadvantages and the costs of using the technology. Innovations that are as yet unproven are poor candidates for mandatory control policy in the near term because technical evaluation of the innovations is incomplete. Unproven innovations also cannot be analyzed in the context of economic incentives policies because the cost-effectiveness of the innovation is not well known.

Like other cautious assumptions in this analysis, omission of recent technological developments from the analysis might lead to underestimates of the extent to which regulatory action can reduce CFC emissions, perhaps especially so for economic incentives because they might make new technologies cost-effective and thus spur their development.

## CFC PRICE ASSUMPTIONS

Unless otherwise indicated, CFC prices are measured at bulk rates, averaged over 1976. The rates are shown in Table 3.5. Some users pay higher prices for smaller unit purchases or for shipping charges. However, insofar as a given absolute increase in bulk rates would result in the same absolute increase in rates for all users, the demand analyses in these studies correctly predict the relationships between CFC use and bulk prices. Prices specified for years other than 1976 are measured in constant (1976) dollars.

## OUTLINE OF THE PRODUCT AREA SUMMARIES

Each product area summary begins by describing the final product, reasons for the use of CFCs in producing the final product, major subcategories within the

Table 3.5

ESTIMATED BULK PRICES FOR VIRGIN CFCs, 1976

| CFC | Bulk Rate Per Pound |
|---|---|
| CFC-11 | .34 |
| CFC-12 | .41 |
| CFC-113 | .62 |
| CFC-114 | .50 |
| CFC-22 | .64 |
| CFC-500 | .62 |
| CFC-502 | 1.11 |
| CFC-125a | 1.16 |

SOURCES: Most estimates were provided by DuPont. The estimate for CFC-11 was drawn from data received in survey responses from producers of foam products; the DuPont value of the CFC-11 price is 37 cents.

product area that use CFCs for different reasons or differ in the nature of the emissions process, and basic features of the market forces causing growth or decline in the use of CFCs.

Next, each summary reports the use and emissions estimates for a baseline case that assumes no change in regulatory policy through 1990. In the interest of brevity, the methodologies underlying the estimates are described in a cursory fashion; important assumptions are noted, but in cases where complex simulation models are used, no attempt is made to provide all the information required to permit the reader to duplicate the methods of calculation. Appendixes amplify on the models used to analyze solvents and rigid and flexible foams. Several IR&T publications that document the models used by IR&T are cited in the bibliography.

The third topic in each summary is a description of the final product market, the number of firms in it, and their locations, employment levels, and other characteristics. Although the information is often quite limited, it does provide some background against which to assess likely user responsiveness to various regulatory strategies.

Options for reducing CFC emissions are the fourth topic of the summary. These are opportunities available to firms or final product consumers to limit emissions, and are not necessarily good candidates for mandatory controls. In discussing the options, we identify those that might be induced by higher CFC prices, those that are included in the benchmark candidates for mandatory controls, those that would be so difficult to enforce that their effectiveness as mandatory controls is questionable, and those whose major effects on emissions would occur after 1990, causing them to be excluded from the set of benchmark control candidates.

The fifth topic is derivation of the product area CFC demand schedule. These schedules provide fundamental insight about the relative costs of alternative options for reducing emissions, and thus provide important background information for assessing the implications of mandatory control policies. The demand schedules are also used later in this report to assess the effects of economic incentive policies.

As a sixth topic, each product area summary estimates the costs to industry and consumers of various candidates for mandatory controls. The discussion of the control candidates includes, as far as possible, an assessment of the "side effects" of regulation, such as increased use of substitute chemicals that might cause worker health or environmental hazards, and increased energy utilization. Control candidates that are not included in the benchmark set (see Secs. I and IV), particularly those that would have a substantial emissions effect after 1990, are discussed to the extent that data permit. Because marketable permit and tax strategies are policy options that are not specific to individual product areas, a discussion of them is reserved for later sections of this report.

# III.A. FLEXIBLE URETHANE FOAMS

## INTRODUCTION

Flexible urethane foam manufacture in the United States began in the 1950s, and the attractive characteristics and low cost of the material have caused it to develop into an important component of furniture, automobile seats, bedding, carpet underlay, and other products where a durable and resilient cushioning material is required. Flexible urethane foams can either be molded into their ultimate shape, or produced in the form of slabstock, a large, continuously made bun that is sawed into pieces several feet high, several feet wide, and six to over 200 feet long. Foam molding is done either by the hot molding process, or by the newer high resiliency molding process, which uses warm molds. In 1977, the estimated total production of flexible urethane foams was about 1,275 million pounds,[1] of which about 65 percent was slabstock and 35 percent was molded. This production used about 38 million pounds of CFC.

The important characteristics of flexible foams are imparted by blowing agents, which form the holes (or cells) in the foam and give it its flexibility. In all flexible urethane foams, the primary blowing agent is carbon dioxide, which is formed by the reaction of water and toluene diisocyanate (TDI). Foams with lower densities than are possible by water blowing (as it is called) require an auxiliary blowing agent. The two most often used auxiliary blowing agents are CFC-11 and methylene chloride, and these are used in the range of less than five percent to about 14 percent of the input chemicals depending upon the product manufactured and which auxiliary agent is used; it takes fewer pounds of methylene chloride than CFC to make the same type of product.

Just as flexible urethane foams can be categorized as either slabstock or molded foams, they can also be categorized as water blown (without an auxiliary blowing agent), CFC blown, or methylene chloride blown. Data to estimate the present distribution of these types are incomplete, but a rough percentage breakdown is shown in Table 3.A.1.

CFC emissions from flexible polyurethane foams are prompt. That is, essentially all the CFC disappears from the freshly made foam in a matter of hours or a few days. This means that annual CFC emissions are virtually identical to CFC consumption in manufacturing the foam, and that the emissions occur at the physical location of the manufacturing facility.

The growth of output from the flexible urethane foam industry between now and 1990 is variously estimated between three and eight percent per year. Various forces acting on the molded foam portion of the market make projections of the CFC use somewhat uncertain, but a reasonable presumption is that the same growth rates apply. Driving the growth in flexible foam markets is the expectation of greater than five percent growth in furniture and bedding markets, over four percent in the transportation market, and over 10 percent for carpet underlay and

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[1] Based on estimates by chemical suppliers.

Table 3.A.1

**APPROXIMATE DISTRIBUTION OF FLEXIBLE FOAM OUTPUT BY TYPE OF AUXILIARY BLOWING AGENT**

(Percent of total output, by weight)

<table>
<tr><th>Blown by:</th><th>Slabstock</th><th>Hot Molded</th><th>HR Molded</th><th>Total</th></tr>
<tr><td>Water</td><td>20</td><td colspan="2">20</td><td>40</td></tr>
<tr><td>CFC</td><td>27</td><td>7</td><td>8</td><td>42</td></tr>
<tr><td>Methylene chloride</td><td>18</td><td>0</td><td>0</td><td>18</td></tr>
<tr><td>Total</td><td>65</td><td colspan="2">35</td><td>100</td></tr>
</table>

SOURCES: Estimates from marketing data from the following: Mobay Chemical Company (see Upjohn, 1977b); Mobay (1978); Allied Chemical Company, Statement to EPA, October 25-27, 1977; Olin Chemicals Group, private communication.

packaging, which are both relatively small uses. An approximate breakdown of foam consumption by final product is given in Table 3.A.2.

## USE AND EMISSIONS

Table 3.A.3 presents the historical sales of flexible urethane foams from the approximate date of their commercial introduction to the present, together with the ranges of future sales projections given by industry sources. Industry sources do not project sales past 1982. For analytical use, we have linearly extended the industry projections to 1990, and produced maximum and minimum projections that reflect the uncertainties inherent in such projections. The band of uncertainty is wide enough to accommodate different assumptions about rates of market saturation and rates of growth of GNP.

The data in Table 3.A.3 may be translated into CFC use projections by applying assumptions about the average CFC content of the foam. As noted above, foam is made by three different processes: the water blown foams use no auxiliary blowing agent, and some of the foam that does use an auxiliary blowing agent does not use CFC. At present, the ratio of CFC use to the weight of total industry foam output is three percent. This will probably decline to about 2.75 percent in 1990 due to greater use of the high resiliency (HR) process, in making molded foam; the HR process uses less CFC than the hot molding process. Applying the three percent factor up until 1977 and then assuming a linear transition to the 1990 factor of 2.75 percent yields the results for CFC use shown in Table 3.A.4. Since the emissions are prompt, Table 3.A.4 also represents emissions of CFC.

## Table 3.A.2

## DISTRIBUTION OF FLEXIBLE FOAMS USE AMONG FINAL PRODUCTS MARKETS, 1977

| Market | Percentage by Weight |
|---|---|
| Furniture | 38 |
| Transportation | 29 |
| Bedding | 15 |
| Prime carpet underlay | 12 |
| Packaging | 2 |
| Textiles | 2 |
| Other | 2 |

SOURCES: Mobay Chemical Company (see Upjohn, 1977b); Mobay (1978); Olin Chemical Group, private communication.

## Table 3.A.3

## ESTIMATED HISTORICAL AND PROJECTED FUTURE FLEXIBLE URETHANE FOAM PRODUCTION

(Millions of pounds)

| Year | Production |
|---|---|
| 1960 | 86 |
| 1965 | 241 |
| 1966 | 307 |
| 1967 | 356 |
| 1968 | 480 |
| 1969 | 520 |
| 1970 | 618 |
| 1971 | 655 |
| 1972 | 746 |
| 1973 | 955 |
| 1974 | 979 |
| 1975 | 974 |
| 1976 | 1,121 |
| 1977 | 1,275 |
| ... | ... |
| 1980 | 1,420-1,690 |
| ... | ... |
| 1982 | 1,696-2,137 |
| ... | ... |
| 1990 | 1,960-3,240 |

SOURCES: Bedoit (1974); Mobay Chemical Company (see Upjohn, 1977b); and Mobay (1978); Upjohn (1975, 1976, and 1977); Allied Chemical Company, Statement to EPA, October 25-27, 1977; Olin Chemical Group, private communication.

Table 3.A.4

ESTIMATED CFC USE AND EMISSIONS IN FLEXIBLE URETHANE FOAM PRODUCTION[a]
(Millions of pounds)

| Year | Use/ Emissions |
|---|---|
| 1960 | 2.6 |
| 1965 | 7.2 |
| 1966 | 9.2 |
| 1967 | 10.7 |
| 1968 | 14.4 |
| 1969 | 15.6 |
| 1970 | 18.5 |
| 1971 | 19.7 |
| 1972 | 22.7 |
| 1973 | 28.7 |
| 1974 | 29.4 |
| 1975 | 29.2 |
| 1976 | 33.6 |
| 1977 | 38.3 |
| ... | ... |
| 1980 | 42.9-50.7 |
| ... | ... |
| 1982 | 50.0-63.0 |
| ... | ... |
| 1990 | 53.9-89.1 |

[a] Estimated from Table 3.A.3, as described in text.

## INDUSTRY AND MARKET CHARACTERISTICS

Information about the structure of the industry derives from the responses to confidential questionnaires that were sent to foam manufacturers by the Society of the Plastics Industry in cooperation with this study, together with estimates provided by the chemical suppliers. Because of the relatively limited number of responses to the questionnaire, our characterizations must be viewed as qualitative. There are sufficient differences between molded foam and slabstock that it is worthwhile to describe these separately.

### Slabstock Foam

There are about 50 companies that manufacture flexible slabstock. Roughly one-third of these are large companies, some of which have multiple plants located in various parts of the country. These large companies each have an annual production volume of 20 to 100 million pounds of foam a year, which would imply average CFC use rates per company of 600,000 to three million pounds per year.

About 15 percent of the companies fall into the range of 10 to 20 million pounds of foam production annually, which would imply roughly 300,000 to 600,000 pounds of annual CFC use. The remaining companies are smaller, manufacturing less than 20 million pounds of foam per year. While foam plants may differ in size by a factor of 10 from the largest to the smallest, large foam companies tend to be multiplant companies, with each plant being located close to a market. A large company might have half a dozen plants across the country.

In terms of foam plants, we estimate that there are about 10 plants that are large enough to consume about one million pounds of CFC per year. One or two of these consume two or more times this amount. There are 30 to 60 plants that have an average consumption of 200,000 to 250,000 pounds of CFC per year; a few consume about 500,000 pounds of CFC. Then there are another 30 to 60 plants that use 100,000 to 200,000 pounds of CFC per year.

Slabstock foam is a low value, low density product, and foamers lose their competitive edge if located too far from their markets because of transport costs. This causes foamers to locate in the midst of their markets, which are predominantly furniture, bedding, and carpet underlay. There is a large concentration of furniture manufacturers in the Southeastern United States, and many foam plants are located in North Carolina, Tennessee, Arkansas, and Mississippi. Flexible foam plants are also located in Southern California, another major furniture manufacturing center. Rhode Island, Indiana, New Jersey, Iowa, Massachusetts, Pennsylvania, Maryland, Indiana, and Colorado all have slabstock foam plants, and it can be inferred that there is probably one near every major metropolitan area where there are furniture or bedding manufacturers. As might be expected from the importance of transport costs, little or no flexible foam is imported or exported.

Slabstock foam is not very capital intensive, and the technical know-how is readily available from the chemical suppliers. Thus, an individual with some key accounts in his control and some reasonable financing can enter the business fairly easily. But small foamers complain about the narrow margins they must live with, and just as a few accounts can cause an entry into the market, their loss could cause an exit. While large companies appear to be well established businesses and have been around for a long time, small companies may come and go. To support this impression, we observe that there are several companies whose sole business is the manufacture of equipment for making foams, and whose customers are primarily recent entrants into the foam production business.

Slabstock foam lines are all designed to produce a bun of similar cross section. Because of this, there is a great deal of similarity in the equipment used by large and small foamers, and the difference in plant output is controlled by the number of hours per day that the foam line is operated. A small foamer may operate his line for only one hour per day, possibly even skipping one or more days per week. A large foamer may operate for a full eight hour shift or longer. As a result, foam equipment is being operated on the average in the range of one-third of its capacity. Among the factors that might limit plant output are limited local market size, warehousing and storage space constraints, and transportation costs.

The industry does not appear very capital intensive, requiring about half a million dollars to set up a small foam plant. The chemicals that are fed to the foam line frequently flow at the rate of about $500 worth per minute, implying that in 1,000 minutes (17 hours) of operation, more value in raw materials will pass through the plant than was involved in setting it up. Larger plants often require much more investment because they are vertically integrated so as to process the slabstock into finished shapes for their customers. Our survey indicated that large firms have individual investments in slabstock plants that typically range from $10 to $15 million, with the investment in each of their plants ranging from $2 to $4 million. These same firms have annual sales of $25 to $75 million. The ratio of capital inputs to total production costs seems to run about one to two percent.

Operation of the foam line generally requires about six people. In small plants where the line operates for only a few hours a day, these people are used in warehousing activities when they are not actually running the line. However, the bun product must be cut and trimmed to its final shape before use, and the cutting and trimming operations involve a great deal of hand work. Large multiplant companies, characterized by annual sales in the range of $25 to $75 million and CFC consumption of one million pounds or more, seem to have about 19 employees per million dollars of sales; i.e., a company with annual sales of $52 million would have 1,000 employees connected with foam operations in three to five plants. In these plants, labor represents about 13 percent of the manufacturing cost.

Foam plants that are involved only in slabstock production, without cutting or trimming operations, may have substantially fewer employees. But since the cutting, trimming, and fabricating operations are an essential part of the conversion of the slabstock into a finished and salable product, we must presume that the people involved in these operations are simply on someone else's payroll, such as the furniture manufacturer. In assessing the employment related to slabstock foam, it would be shortsighted to overlook this.

The output of the slabstock industry is closely related to the output of the furniture, bedding, and carpet industries. Originally, materials other than foam were used in furniture cushioning, but these have been largely replaced by foam. Bedding is made both with and without foam, but the desirable characteristics of foam probably mean that penetration of this market will increase. Similarly, the superior quality of foam carpet underlay probably means that penetration will also increase in that market, especially since otherwise worthless scrap foam is rebonded into carpet underlay and sold in competition against other carpet underlays.

CFC use represents only a small part of the final product price, and therefore changes in CFC prices might have only a small effect on the final consumer. For example, in the softest foam usually used in furniture, the CFC presently accounts for about 13 percent of the raw materials cost. For a medium softness foam, the CFC represents only about five percent of material costs. According to furniture manufacturers, foam represents 10 to 15 percent of their manufacturing costs, which means that the CFC accounts at most for about two percent of the furniture manufacturing cost. Thus, changes in CFC price, even if passed through to the consumer at full markup, have little leverage on furniture prices.

Similarly, because the CFC content of carpet underlay is very low, the CFC leverage on its price would be very small.

For bedding, in which expenditures for foam might be the major component of bedding production costs, the situation is different. But even if mattresses used only supersoft foam, the CFC would represent less than 13 percent of the foam cost, and leverage on the price of bedding would be modest.

## Molded Foam

The major consumer of molded urethane foam is the automotive industry, and this fact dominates the economic characteristics of this sector of the foam industry. There are less than 20 companies involved (one source estimates 16), of which half make between 10 and 100 million pounds of foam per year. The balance consists of smaller plants, averaging perhaps five million pounds per year of output.

Whereas large slabstock companies usually have multiple plants, the same is not true for the molded foam companies, primarily because a major portion of their output is destined for a small group of customers in a relatively concentrated location—the automotive industry. Also, the molding process lends itself to automation, and thus some plants are huge. The large size of a few of these plants means that they are also large single point sources of emissions, with several plants emitting between one and four million pounds of CFC per year.

Molded foam plants are found close to automotive assembly plants, with most of the molded foam being made in Ohio, Indiana, Michigan, California, and New England.

Entry into and exit from this market are rare, except perhaps for very small specialty molders. Recent conversions from hot molding to high resiliency molding processes have increased production capacity, and a crude estimate of the unused production capacity of the molded foam industry is about one-third the level of current production.

Molded foam plants do not resemble slabstock plants at all. The equipment is vastly different, with molds on an automated production line that runs through curing ovens, demolding stations, automatic release agent application, mold filling, product crushing, and wire filling operations. The entire line might be computer controlled in order to achieve high production levels and extremely accurate product quality control. We do not have industry-wide estimates of capital costs in typical large molded foam plants, due to limited responses to our questionnaire. But the responses received indicate that the investment and employment characteristics of large molded foam companies may not be too different from their slabstock counterparts having a comparable dollar volume of production. This may result in part because molded parts require much less hand work than the fabrication of slabstock, and also because the value per pound of molded foam output is about two or more times greater than that of slabstock.

The output of the molded foam industry is directly related to the output of the automobile industry, and changes in automobile production can be expected to relate almost exactly to changes in molded foam production.

Molded auto seat bottoms are water blown because of their stiffer character, and thus do not use any auxiliary blowing agents. The seat backs generally use CFC. According to foam molders, the high resiliency process uses about 25 percent less CFC per pound than the older hot molded process. In either case, the CFC is a minor constituent of the material costs. Because the end product is generally an automobile, it is difficult to envisage a perceptible effect on final product retail prices resulting from changes in the price of the CFC used to make the seat backs.

## TECHNICAL OPTIONS TO REDUCE EMISSIONS

Two technical options exist for reducing CFC emissions from the manufacture of flexible urethane foams: substitution of other auxiliary blowing agents, and recovery and recycle of the emitted CFC.

### Substitution Away from CFC

Earlier, we noted that flexible foams are either water blown (using no auxiliary blowing agent), or are blown with either CFC or methylene chloride auxiliary blowing agents. All types of foams that can be water blown already are, so there is no potential for substitution. However, many slabstock foams can be blown with either CFC or methylene chloride, suggesting that CFC emissions could be reduced if methylene chloride were substituted for the CFC—in essence, replacing CFC emissions by those of methylene chloride.

For many grades of slabstock, the materials costs of methylene chloride formulations are lower than those of CFC-based formulations. On the surface, this fact alone might cause the industry to convert from CFC use, but as often is the case, a detailed examination of the factors involved indicates that the situation is not so simple. No better proof of this is needed than the observation that some of the largest manufacturers of slabstock use both auxiliary blowing agents in the same plant, allocating each to the product that they feel can be best made with it, balancing questions of economy and quality.

There are wide ranging and staunchly defended diverse opinions about methylene chloride as a blowing agent. Many foamers argue that quality control of very soft foams is more difficult when using methylene chloride and therefore the scrap rate of the product is higher. Coping with this requires technical skill, and we found at least one multiplant company whose ability to use methylene chloride varied from plant to plant, depending upon the skill of the personnel involved. To counter this perceived disadvantage, methylene chloride manufacturers continue to conduct research designed to enhance the market penetration of this product.

There are also hotly debated questions about the relative safety of methylene chloride. While CFC-11 has a threshold limit value (TLV)[2] of 1,000, methylene chloride has a recommended TLV of 200. Questions of the toxicity of the material have been addressed by the manufacturers of methylene chloride, and their conclusions state that the product is safe to use when properly handled. However, there are strongly held contrary opinions by foamers, and these opinions are part of the reason that many slabstock foamers use only CFC. The fact that they do, and that they coexist with foamers who use methylene chloride, indicate that current cost differences between foams made with the two materials are not sufficient to force the emergence of one or the other as the preferred blowing agent in all foams.

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[2] TLV is expressed in parts per million of a vapor in air. It is the legal maximum average concentration of the vapor to which a worker may be exposed in an eight hour period.

From a technical standpoint, it would be difficult to achieve complete replacement of CFC by methylene chloride. There are a variety of reasons for this that range from the unavailability of methylene-chloride-based formulations for some specialty foams to the inability of some foamers to handle the technical problem of blowing agent conversion. A response to our interim report under the Society of the Plastics Industries' letterhead suggests that perhaps 75 percent of the present use of CFC in slabstock could be replaced by methylene chloride.

There is little difference between a foam plant designed to use methylene chloride and one designed to use CFC. Because of the lower TLV of methylene chloride, ventilation requirements may be more severe. However, foam plant ventilation is usually designed to cope with another of the foam chemicals, TDI, which has a TLV of 0.02. The ventilation installed for this purpose is often sufficient to handle the methylene chloride. For plants where separate ventilation is used in the curing and warehousing areas, higher air flow rates might be required if methylene chloride is used.

Substitution among blowing agents appears less possible in molded foams. Some studies suggest the product that results has quality characteristics that are presently unacceptable,[3] but there does appear to be the potential of blending CFC with 20 percent methylene chloride to obtain a satisfactory product. Other research regarding molded foam is directed at attempts to minimize auxiliary blowing agent use. Recent conversions from hot molding to HR molding have resulted in perhaps a 25 percent reduction in CFC use, and continuing research is seeking to reduce this figure further. In short, there are few pressures to continue to work with methylene chloride in molded foams.

## Recovery and Recycle

The principle behind this technical option is simple. Flexible foams are prompt emitters, losing essentially all of their CFC before they leave the foam plant. If the emitted CFC could be collected and reused, it would reduce emissions in direct proportion to the collection efficiency.[4] Flexible slabstock lines appear particularly suited for this process, since the foam is made in a long tunnel equipped with ventilation fans, which collect the exhaust gases and discharge them outside the plant. Recent measurements made by DuPont indicate that in a well-designed modern slabstock plant, the CFC collection efficiency of these ventilation systems may already be between 33 and 53 percent. Molded foam lines may also already collect similar percentages in the ventilation system at the demolding stations.

Once collected, CFC may be recovered by carbon adsorption. In this process, the CFC laden air is passed over beds of specially prepared carbon. The CFC adsorbs onto the carbon, and the CFC-free air then is exhausted. After the bed has reached its capacity, the carbon is desorbed with steam, and the CFC is separated for recycling purposes. Adsorption technology is well established, and its use in CFC-11 recovery and recycle is successfully practiced in some nonfoam industries, where it has proved economical. Experience with flexible slabstock lines appears limited to one experiment that was conducted in 1968, and which was deemed a failure for economic reasons.

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[3] One result is that the surface is sufficiently less slick that the cushions cannot be stuffed into their covers. Another is that surface imperfections, such as bubbles, become objectionable.

[4] Collection efficiency refers to the efficiency of the ventilation system in capturing the CFC before it is dissipated to the atmosphere. Ventilation systems already exist on all foam lines, for control of the TDI.

Reviewing the applicability of the adsorption process to slabstock lines reveals that there are contaminants in the vented gas that interfere with the carbon bed. For example, TDI "poisons" the bed so that the carbon will not adsorb the CFC. Other contaminants, such as amines, surfactants, and aerosols, may have similar effects, but this is not now known. The situation requires that the exhaust gases from the foam line first be treated to remove the interfering contaminants, and then be passed over the carbon beds.

The cost of this pretreatment step is presently unknown, and consequently, an accurate appraisal of the economics of the process is difficult to make. It is clear, however, that recovery and recycle equipment is more likely to be economical in large foam plants, in which there is more CFC to recover, than in small ones. This is because the capital investment may not be much different for different sized plants (like the slabstock line itself) and because most of the costs of a recovery and recycle system are capital-related ones. If the volume of exhaust gas treated is 20,000 cubic feet per minute (CFM), which might be representative of a well-designed slabstock line, the total capital investment might vary between $480,000 and $1,440,000,[5] depending upon the cost of removing the contaminants from the gas stream.

## CFC DEMAND SCHEDULES

Our analysis of the demand for CFC-11 by flexible foamers presumes that they attempt to make each type of foam in the most cost-effective manner, taking into account such considerations as the desired density, resiliency, and overall quality of the foam. For some foams, the only feasible way to reduce production costs when virgin CFC-11 prices rise is to recover and recycle the CFC; the analysis presumes that this option becomes economically attractive when the virgin CFC-11 price is high enough that the savings from using recycled CFC offset the costs of installing and operating recovery and recycling equipment. For other foams, the use of methylene chloride is also a feasible option, one that would be employed when the cost of chemical substitution is lower than continuing to use CFC at a higher price, even with recovery and recycling. Given estimates of the costs of recovery and recycling and the costs of methylene chloride substitution, it is possible to infer the CFC-11 prices at which each of these options becomes economically attractive for different foamers and types of foams, and thereby to infer the amount of reduction in CFC-11 use at each level of increase in CFC prices. The analysis by which these inferences are drawn is described here and amplified in Appendix D.

If the CFC-11 price rises but there is no technique available for producing a foam at lower cost, the CFC will still be used and foamers making that type of foam will charge their customers higher prices to cover the higher foam production costs. Even in this case, we do not expect consumers to buy much less of the foam. CFC accounts for a small fraction (4 to 11 percent) of total foam production costs and an even smaller fraction of the costs of final consumer products made with foam. For the CFC price increases under consideration here, even complete pass-through of cost increases would have little effect on consumer prices and, by the reasoning presented in Sec. II, would have little if any effect on sales of foams. And if there is a way to avoid some of the increase in foam production costs (e.g., by converting to methylene chloride or by recycling the CFC), then the amount of cost increase passed on to the final consumer would be less. In short, none of the CFC price increases examined here would significantly reduce the production of flexible foams. All of the predicted reductions in CFC use would come about by implementing recovery and recycle or chemical substitution while maintaining the overall level of foam output.

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[5] Based on estimates by Vic Manufacturing Company and DuPont of $24 to $72 per CFM, installed.

Recovery and recycle is a potential response to higher prices for virtually all users of CFC-11. The demand schedules presented below assume that the installed capital cost of recovery and recycle equipment is $960,000 per plant (the midpoint of available estimates) and that 50 percent of initial CFC use is recovered and reused on average. For the flexible foam industry, an investment criterion of a 4.2 year payback period is assumed.[6] In addition, recovery and recycle increases plant operating costs by an estimated $26,800 annually[7] plus $.014 per pound of recovered CFC due to the energy requirements of the recovery unit. Because most of the costs of recovery are independent of the amount of CFC recovered, this option is much more attractive for plants that use large amounts of CFC.

For most flexible slabstock producers, conversion to methylene chloride is also a potential response to higher CFC prices. Conversion apparently involves no significant capital expenditures, but there are at least two deterrents to the use of methylene chloride in flexible foams now blown with CFC. According to industry sources, methylene chloride conversion increases the difficulty of controlling some foam formulations, resulting in higher levels of rejected product (or scrap). Consequently, foam lines converted to methylene chloride require greater amounts of material inputs to produce a given amount of foam output. Available evidence suggests that this material cost is smaller for larger slabstock producers, who have superior technical expertise for adjusting methylene chloride foam formulations. In addition, some slabstock producers are reluctant to use methylene chloride because they suspect it may affect worker health, or might at some future time be regulated.

Because these factors discourage methylene chloride use, slabstock producers are not expected to convert voluntarily to methylene chloride unless the price of CFC-11 rises. For smaller slabstock plants, the demand analysis adopts the assumption that methylene chloride conversion will not occur unless the cost of materials contained in CFC blown final foam output is 20 percent higher than the cost of materials in an identical amount of methylene chloride blown foam output. For large slabstock plants (where CFC use is greater than one million pounds annually), we assume that conversion will occur when the materials cost in CFC blown final foam output is 12.5 percent greater. The assumptions for both large and small plants are somewhat cautious, being more likely to overstate than understate the CFC prices at which conversion would occur.

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[6] This investment criterion is equivalent to a 10 year useful life for the equipment and a pretax opportunity cost of capital of 20 percent annually.

[7] These costs include $0.08 per CFM for maintenance, based on information from a producer of carbon adsorption units, $6,000 for labor, and insurance at two percent of the capital cost, based on DuPont (1978a).

The cost of conversion to methylene chloride also depends upon the type of foam produced. In the demand analysis, we distinguish between two types of flexible slabstock—medium soft and soft foams.[8] Because medium soft foams use greater amounts of nonblowing agent materials per pound of CFC, the costs imposed by the higher scrap rates associated with methylene chloride are greater for these products. Consequently, if scrap rates for both types of foam are similarly affected by conversion to methylene chloride, a higher CFC price is required to induce conversion by producers of medium soft foams.

Table 3.A.5 presents the distribution of CFC use levels employed in the flexible foam demand simulation.[9] Because incentives for CFC recovery depend upon the level of CFC use, the demand analysis requires information on the distribution of CFC use per plant. The analysis distinguishes five types of flexible foam production facilities: large and small molded plants and large, medium, and small slabstock plants. In addition, for slabstock plants, we assume one-half primarily produce medium soft products and one-half primarily produce soft products.

Table 3.A.5

APPROXIMATE DISTRIBUTION OF CFC USE PER PLANT BY TYPE OF FLEXIBLE URETHANE FOAM[a]

| Type of Foam, Plant size | CFC USE Per Plant (thousands of lb) | Share of Total CFC Use (percent) |
|---|---|---|
| Molded foam | | |
| Large plants | 2,500 | 20 |
| Small plants | 500 | 16 |
| Slabstock | | |
| Large plants | 1,200 | 34 |
| Medium plants | 225 | 18 |
| Small plants | 150 | 12 |

[a] Based on Tables 3.A.1, 3.A.3, and industry sources.

For producers of molded flexible urethane foam, the only possible responses to higher CFC prices (other than reduced output levels) are paying the higher price or CFC recovery. On the basis of the recovery costs described above, recovery and recycle appears cost-effective at or near current CFC-11 price levels for large molded plants, which use extremely large amounts of CFC-11.[10] For smaller producers of molded foam, the total value of recovered CFC is only 20 percent of that for large CFC users, and CFC recovery will probably not occur unless the price of CFC-11 exceeds $1.04 per pound.

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[8] Harder flexible urethane foams are not commonly produced with an auxiliary blowing agent.

[9] While the actual size distribution of plants is somewhat more diverse than Table 3.A.5 indicates, these data appear to be a reasonable summary of the variety of plants in the industry and simplify the demand schedule estimation procedure considerably.

[10] Recovery appears economical at current prices for these large CFC users even at the upper-bound estimate of capital costs ($1.44 million per plant). There are several possible explanations of why

Flexible slabstock producers may respond to higher CFC prices in several ways. Possible responses include: pay higher CFC prices; recover CFC; convert to methylene chloride in products where this blowing agent is technically feasible and pay higher CFC prices for the remaining output;[11] and convert to methylene chloride where feasible and recover and reuse both blowing agents. Whereas conversion to methylene chloride requires no fixed investment, an initial investment in recovery and recycle equipment must be reimbursed by materials cost savings over a period of time. Hence, whether conversion, recycling, or both will be implemented depends upon where the regulated price of CFC-11 is expected to stabilize (referred to below as the "long-run" CFC-11 price).

For large slabstock plants, no emissions-reduction activity is expected at long-run CFC-11 prices below $0.44 per pound.[12] Above this price level, reducing CFC use (and emissions) is a profitable activity. From the cost parameters presented above, at prices from $0.44 to $0.61 per pound, all large slabstock plants would minimize production costs by employing CFC recovery equipment. If firms expect a regulated price of CFC-11 from $0.61 to $1.13, methylene chloride conversion (rather than CFC recovery) will occur in large plants that primarily produce soft foam products, reducing emissions by 75 percent. However, for large slabstock plants that primarily produce medium soft foams, CFC recovery always results in lower costs than methylene chloride conversion in the range of CFC prices considered in this study. Finally, if firms can recover methylene chloride as well as CFC-11 (as available evidence suggests), the analysis suggests that at prices above $1.13 per pound large slabstock plants that produce softer foams would convert to methylene chloride where possible and purchase recovery equipment in order to reuse both auxiliary blowing agents.

For smaller slabstock producers, CFC recovery is an extremely unlikely outcome of higher CFC prices regardless of the type of foam produced because of their relatively low CFC use levels per plant.[13] Instead, we expect small slabstock producers to respond to higher CFC prices by switching blowing agents. Methylene chloride costs less per pound than CFC-11 and 15 percent less blowing agent is

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recovery does not occur at the present time. First, firm managers may be uncertain about what overall recovery efficiencies are actually achievable and about actual volumes of exhaust gas to be treated. Second, some cost variables may have been omitted from the analysis. Third, and perhaps most important, the uncertain regulatory climate in the recent past may have discouraged recovery efforts. For example, despite the seemingly attractive economics, recovery would be discouraged if firms anticipated a future ban on CFC blowing agents, as occurred in the aerosol regulations, or if substantial subsidies were anticipated for future purchases of recovery equipment. In any case, all available evidence strongly suggests that CFC recovery in large molded foam plants would be among the first responses observed as the CFC price increases.

[11] On the basis of information from the Society of the Plastics Industry, we assume that 25 percent of each plant's output cannot be converted to methylene chloride. Other industry sources quoted smaller percentage estimates.

[12] Blowing agent prices appear to vary from producer to producer. As a base case, the prices of CFC and methylene chloride are assumed to be $0.34 and $0.22 per pound.

[13] For smaller slabstock producers, CFC recovery does not result in lower production costs than methylene chloride conversion at any CFC price, on the basis of the cost parameters defined above. If a small plant cannot convert any of its output to methylene chloride, CFC recovery would be induced at a CFC price of $2.29 for medium slabstock plants and $3.42 for the smallest slabstock plants in Table 3.A.5.

required to produce a given amount of final product (ignoring scrap). However, because of the material and other costs associated with methylene chloride, conversion by small plants that produce softer products is not expected unless the long-run CFC price exceeds \$0.68 per pound. At this price, these producers convert 75 percent of their CFC blown production to methylene chloride and are assumed to incur higher prices for the remaining CFC. For small plants that primarily produce medium soft foams, conversion to methylene chloride is not expected unless the CFC price reaches \$1.52 per pound.

Finally, higher CFC prices would also induce improved collection efficiencies for CFC recovery in both molded and slabstock plants. Although existing plants appear to collect a significant fraction of CFC use at central points in their ventilation systems, plants have not been designed with this purpose in mind. Higher CFC prices would create strong incentives to recycle as much CFC-11 as possible, given that a firm employs recovery equipment. While exact information on the costs of improving collection efficiencies is unavailable, in some cases relatively modest capital costs may be involved. However, even assuming that capital costs are high leads us to expect that a CFC-11 price of about \$1.50 would be sufficient to induce an increase in overall recovery efficiencies to 80 percent of CFC use.[14]

Table 3.A.6 presents the demand schedule for CFC use in flexible urethane foams, based on the above analysis and assumptions. According to the analysis, an increase in the CFC price of only 10 cents per pound will reduce CFC use by an estimated 27 percent. If CFC-11 prices were to double, CFC use in flexible foam products would decline by over 42 percent, with most of the emissions-reduction activity occurring in large foam plants. Because flexible foams are prompt emitters, the annual use reductions in Table 3.A.6 equal annual reductions in CFC-11 emissions.

The increase in CFC-11 prices required to induce the use of a technical option measures the cost of the option per unit reduction in CFC-11 use. Thus, the first technical option to be induced, recovery in large molded and slabstock plants, reduces use by 12.6 million pounds at a cost of just 10 cents per pound of reduction. However, achieving further reductions imposes increasingly higher costs per unit reduction in CFC use. For example, the cost of the last technical option that is induced by higher prices (methylene chloride conversion by small slabstock plants producing medium soft foam) costs \$1.18 per pound.

In part, the higher costs required for each additional emissions-reduction activity reflect the differential economic impact of restrictions on CFC use for large and small foamers. Because of their lack of sufficient technical expertise for using methylene chloride and lack of large size for CFC recovery, small plants find it relatively costly to reduce CFC use. Thus, while large foamers find it cost-saving to substitute away from CFC at relatively low CFC prices, small foamers will absorb the full impact of higher CFC prices until the CFC-11 price increase is substantial.

The demand schedule of Table 3.A.6 can be used to derive information regarding the use of methylene chloride. At a CFC price of \$0.68, we estimate methylene chloride use will be at least 11 million pounds higher than in the baseline case in

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[14] For a molded foam producer using 500,000 pounds of CFC annually, modifying the plant to achieve this higher collection efficiency at a CFC price of \$1.50 will be profitable so long as the capital costs involved are less than an estimated \$920,000.

## Table 3.A.6

### CFC-11 Demand Schedule for Flexible Urethane Foam, 1980 and 1990[a]

(Millions of pounds)

| CFC-11 Price (1976 $ per lb) | Induced Activity[b] | 1980 | | 1990 | |
|---|---|---|---|---|---|
| | | CFC Reduction[c] | Total CFC Use[d] | CFC Reduction[c] | Total CFC Use[d] |
| 0.34 | None | -- | 46.8 | -- | 71.5 |
| 0.44 | Large MD and all large SL plants recover | 12.6 | 34.2 | 19.3 | 52.4 |
| 0.61 | Large SL, SF plants convert | 2.0 | 32.2 | 3.0 | 49.2 |
| 0.68 | Smaller SL, SF plants convert | 5.3 | 26.9 | 8.0 | 41.2 |
| 1.04 | Small MD plants recover | 3.7 | 23.2 | 5.7 | 35.5 |
| 1.13 | Large SL, SF plants recover and convert | 1.0 | 22.2 | 1.5 | 34.0 |
| 1.50 | Improved collection efficiency | 8.0 | 14.2 | 12.3 | 21.7 |
| 1.52 | Smaller SL, MF plants convert | 5.3 | 8.9 | 8.0 | 13.7 |

[a] See text for explanation of calculations. Estimates based on distribution of CFC use in Table 3.A.5.

[b] MD denotes molded foam, SL denotes flexible slabstock, SF denotes soft slabstock foam, and MF denotes medium soft slabstock foam.

[c] Shows incremental reduction induced at indicated price.

[d] Shows total CFC-11 use at indicated price level.

1980 and nearly 17 million pounds higher in 1990. However, at prices in excess of $1.13 for CFC-11, methylene chloride may be recovered along with CFC-11 by large slabstock plants. In this CFC price range, methylene chloride use is higher than in the baseline forecast, but only by about eight million pounds in 1980 and 13 million pounds in 1990. Finally, at CFC-11 prices in excess of $1.52, we estimate that methylene chloride use will increase by about 12 million pounds in 1980 and by over 18 million pounds in 1990.

## MANDATORY CONTROL CANDIDATES

The two technical options for reducing CFC-11 use and emissions from flexible foams—recovery and recycle and methylene chloride conversion—are discussed here as candidates for mandatory control policy. The first of the options meets the criteria stated in Sec. I for inclusion in the benchmark set of mandatory controls; as explained below, the benchmark analysis presumes that CFC recovery and recycle would be implemented in the absence of any other regulatory restrictions limiting the use of methylene chloride, thus allowing foamers who would find the CFC recovery mandate especially costly to avoid the mandate by converting to methylene chloride. For reasons given below, methylene chloride conversion is not included in the benchmark controls, though the implications of required conversion are spelled out here.

## Required Recovery and Recycle

A recovery and recycle mandate meets all the criteria for inclusion in the benchmark controls: The mandate appears enforceable because once each plant has made the investment in recovery equipment it is cost-saving to use the equipment rather then to let it stand idle; hence, enforcement consists of making sure each plant acquires the necessary equipment. The mandate would be effective in reducing CFC-11 emissions by 1990 because annual use equals annual emissions in the flexible foams product area. There are also sufficient data about recovery and recycle to make a reasonable judgment about the costs and effectiveness of a recovery mandate. Moreover, the recovery option is technically feasible for all types of foams, so a recovery mandate would not require exemptions in order to avoid eliminating the production of certain foams.

A CFC recovery mandate for flexible foams could be implemented as a new source standard, requiring compliance only in plants constructed after a specified date, or as a retrofit standard, requiring compliance by existing plants as well. However, new source standards are unlikely to be an effective means of controlling emissions from flexible foam plants. These plants typically operate for only one to five hours per working day and appear capable of significant increases in output levels. Because new source standards dramatically increase production costs in new plants relative to existing facilities, a likely outcome is that existing foam plants would be operated more hours than otherwise and industry growth would occur primarily through expansion of output in existing plants where emissions controls are not required.

In contrast, mandatory controls requiring recovery in existing as well as in new plants do not increase production costs in new foam plants relative to old plants, and no incentives are created to avoid new plant construction in order to circumvent the intent of the regulation.[15] As a result, while new source standards would have little impact on pre-1990 CFC emissions in this industry, retrofitting could significantly reduce emissions levels. The following analysis concentrates on mandatory controls for both existing and new plants.

Under a CFC recovery mandate, producers of molded flexible urethane foams would purchase recovery equipment and reduce emissions by about 50 percent. For large molded CFC users, recovery currently appears economical (or nearly so) and no compliance costs for the regulation are imputed to these firms. For smaller molded foam plants, a CFC recovery mandate increases the fixed costs of production by an estimated $256,000 annually (including amortized capital expenses, insurance, and other costs) and reduces material expenditures by only $81,000, resulting in a net cost to each plant of approximately $175,000 annually, or $0.70 per pound of CFC emissions avoided.

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[15] Currently, several factors, such as transportation and warehousing costs, constrain optimal plant output levels. A CFC recovery mandate increases the fixed costs of production while reducing variable costs by substituting reclaimed for virgin CFC. Consequently, optimal plant output levels under the mandate would increase slightly (see Sec. II) and there would be fewer flexible urethane foam plants than in the baseline case. However, this does not imply that plant closings would occur. Rather, fewer plants would be constructed to meet the anticipated growth of the industry.

For large flexible slabstock plants, the use of mandated CFC recovery devices also increases fixed production costs by $256,000 annually. However, because of the greater quantities of CFC recovered, material expenditures are reduced by nearly $196,000, and the net annual costs of the mandate are estimated at about $60,000, or $0.10 per pound of emissions avoided.

On the basis of the earlier demand analysis, firms that produce flexible slabstock in smaller plants will not respond to a recovery mandate by purchasing recovery equipment. Rather, if allowed to do so, they will convert foam lines to the use of methylene chloride. For softer foam output that can be converted, the costs of substituting methylene chloride may be as high as $65,000 per plant annually, or $0.34 per pound of CFC emissions avoided.[16] For smaller slabstock plants that primarily produce medium soft products, the estimated costs of conversion are much higher, although still less than if these plants were to recover their CFC. For these plants, the recovery/recycle mandate could impose costs as high as $221,000 per plant, or $1.18 per pound of emissions avoided.

Small plants that produce flexible slabstock would probably lose any foam markets that depended on products that cannot be converted to methylene chloride at the present time. The most likely outcome is that these markets would be supplied by increased output from larger plants. Consequently, this analysis does not estimate the costs of forgone production of these products.

Table 3.A.7 summarizes the costs of mandated CFC recovery for the flexible urethane foam industry, assuming that small slabstock plants convert to methylene chloride. With an overall recovery efficiency of 50 percent, the mandate could reduce annual emissions by over 40 million pounds in 1990 and cumulative emissions by nearly 370 million pounds from 1980 through 1990.

Estimates of costs in Table 3.A.7 implicitly assume that the number of flexible foam plants in each category increases proportionately with industry output.[17] The total estimated costs of a CFC recovery mandate are $10.9 million in 1980 and $17.0 million in 1990 (in 1976 dollars), averaging about $0.41 per pound of emissions avoided. From 1980 to 1990, the present value of the estimated costs generated by the regulation are $93.3 million (discounted at 11 percent annually).

The above analysis assumes that no regulatory action is taken to discourage the use of methylene chloride blowing agents. If a CFC recovery mandate required that small slabstock foamers use CFC recovery, rather than convert to methylene chloride, the costs of the regulation would be higher. Assuming annual CFC use levels of 225,000 pounds for medium sized plants and 150,000 pounds for small plants, the

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[16] Based on cost assumptions presented at p. 54.

[17] Because average output per plant is likely to increase slightly, and because the net costs of CFC recovery decrease as plant size increases, the assumption of constant per plant output levels over time biases cost estimates upward.

## Table 3.A.7

## EFFECTS OF MANDATED CFC RECOVERY IN FLEXIBLE URETHANE FOAM PLANTS[a]

| Type of Foam, Plant size | Emissions Reduction (millions of lb) | | | Total Compliance Costs (millions of $) | | | Cost per lb[d] ($) |
|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 1980-1990[b] | 1980 | 1990 | 1980-1990[c] | |
| Molded | 8.3 | 12.6 | 114.7 | 2.4 | 3.8 | 21.3 | 0.31 |
| Large plants[e] | 4.6 | 7.0 | 63.8 | -- | -- | -- | -- |
| Small plants | 3.7 | 5.6 | 50.9 | 2.4 | 3.8 | 21.3 | 0.70 |
| Slabstock | 18.2 | 27.9 | 253.8 | 8.5 | 13.2 | 72.0 | 0.47 |
| Large plants | 7.9 | 12.1 | 110.3 | 0.7 | 1.2 | 6.6 | 0.10 |
| Medium and small plants[f] | 10.3 | 15.8 | 143.5 | 7.8 | 12.0 | 65.4 | 0.76 |
| Total | 26.5 | 40.5 | 368.5 | 10.9 | 17.0 | 93.3 | 0.41 |

[a] See text for explanation of calculations. Assumes mandate applies to existing and new plants, and no restrictions on methylene chloride use. Cost estimates are in constant (1976) dollars.

[b] Cumulative emissions reduction from 1980 to 1990, inclusive.

[c] Present value of annual 1980 to 1990 net costs, discounted at 11 percent.

[d] Calculated from individual plant data.

[e] Recovery assumed economic at or near current CFC prices.

[f] Emissions reductions and estimated costs based on methylene chloride conversion, rather than CFC recovery. Estimates include plants producing both medium soft and soft flexible foams.

net costs of using recovery equipment are an estimated $1.95 and $3.08 per pound of emissions avoided for these plants, respectively.[18] While the level of emissions reduction declines because only 50 percent of CFC emissions are assumed recovered, total compliance costs for these firms increase sharply to about $17 million in 1980 and $25 million in 1990.

In short, if a CFC recovery mandate is designed to force smaller slabstock foam plants to purchase and use recovery equipment, the net costs imposed on all smaller plants would be more than five times the total costs incurred by all other firms combined, despite the fact that the total emissions reduction of the larger plants would be twice as great. Obviously, it is unlikely that small plants could survive such an extreme cost disadvantage. Consequently, under a CFC recovery mandate combined with restrictions on the use of methylene chloride, many small plants may be forced to close. Currently, there are at least 60 plants that might be affected, located in all regions of the country. The markets previously supplied by this sector of the industry would be gained by nonfoam substitute products or, as appears more likely, by larger foam plants.

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[18] Note that the costs of CFC recovery and recycle are not affected by the type of foam produced.

Ultimately, the cost impacts of mandated CFC recovery will be born primarily by the final consumers of products that use flexible urethane foam. Although the total costs of the control strategy (assuming small slabstock plants convert to methylene chloride) are significant through 1990, the impact on prices of individual products will probably be small. In markets where foam is only one component of the final good, final product prices would probably rise by no more than one percent for furniture products and by much less in the transportation markets. In other cases where foam makes up a larger fraction of final product costs, such as foamed mattresses and carpet underlay, the relative increase in prices will be larger. The cost of the flexible foam itself would increase by less than five percent on average, with greater increases for smaller slabstock and molded plants than for other producers.

The employment effects of mandated CFC recovery are exceedingly difficult to estimate. However, even under the assumption of completely inelastic foam demand, the above analysis suggests that some smaller plants, which are placed at a relative cost disadvantage, may reduce employment levels or close down as foam markets are lost to larger competitors. Although total industry employment may not be significantly affected, temporary employment dislocations will almost certainly occur, affecting perhaps as many as 1,500 workers.

### Mandated Methylene Chloride Conversion

At present, most molded foams and some slabstock foams cannot be made with methylene chloride. Thus, unless some foam products are exempted, a methylene chloride conversion mandate might amount to a product ban on 25 percent of slabstock foam and virtually all molded foams, which together currently account for over half of all CFC blown output. In these segments of the industry, the promulgation of a conversion mandate would result in possibly severe employment effects as well as substantial losses in terms of the value of forgone output. Because product bans are not a focus of the current analysis, we do not include the unexempted conversion mandate in the benchmark mandatory controls.

For (slabstock) foams that can be converted to methylene chloride, an effectively enforced conversion mandate would cost the affected firms a total of $13.0 million in 1980 and $19.7 million in 1990, with small plants accounting for nearly two-thirds of the total.

However, it is unlikely that a conversion mandate that exempts certain foams could be effectively enforced. Since an individual slabstock plant produces several different types of foams, exemptions for slabstock foams that cannot be made with methylene chloride would allow both CFC-11 and methylene chloride blowing agents to be used in the same plant. Because the alternative blowing agents can be used on the same production line, enforcement of a regulation involving exemptions would be difficult and costly, requiring a constant threat of inspection at every plant. Consequently, the option of mandating methylene chloride conversion is omitted from the benchmark set of mandatory controls on the grounds that it does not meet the enforceability criterion.

## CONCLUSIONS

Flexible urethane foam plants are a significant source of CFC emissions. Total emissions from flexible urethane foam are among the largest of all nonaerosol CFC uses and may be as high as 90 million pounds of CFC-11 in 1990. Moreover, each plant represents an extremely large point source of emissions, with hundreds of thousands of pounds of CFC-11 used and emitted annually per facility.

In contrast to many other nonaerosol CFC uses, emissions from flexible urethane foam appear susceptible to regulatory action. Either CFC recovery or methylene chloride conversion could substantially reduce CFC releases to the atmosphere, and CFC recovery appears to be an enforceable candidate for mandatory controls. However, the most efficient means of reducing emissions for a flexible foam producer depends upon the characteristics of the firm, such as the level of CFC use per plant and the types of foam products produced. Thus, mandatory recovery would impose vastly different levels of costs on different firms.

The use of CFC in foam products is sensitive to the price of CFC-11. The analysis suggests that substantial reductions in use can be induced by moderate price increases, and that total industry use could be reduced by as much as 80 percent if the price of CFC-11 increased by slightly more than $1.00 per pound.

# III.B. SOLVENTS

## INTRODUCTION

The solvents product area encompasses almost all domestic applications of CFC-113 and does not involve substantial use of any other CFC.[1] Table 3.B.1 reports the distribution of CFC-113 among its various applications in 1976. By far the largest category of applications is cleaning and drying, which accounted for 84 percent of CFC solvent sales. Dry cleaning, at less than four percent of sales, is not a major use category but is significant because of impending regulations on alternative dry cleaning agents. The remaining uses of CFC-113 are described by DuPont as "solvent-related" uses. They are included in this analysis, along with the 2.5 million pounds of CFC-113 used in specialized refrigeration applications, to encompass the total market for CFC-113.

Table 3.B.1

DOMESTIC SALES OF CFC-113 FOR CATEGORIES OF SOLVENT-RELATED USES, 1976

| Use Category | Domestic Sales (millions of lb) | |
|---|---|---|
| Cleaning and drying (total) | | 55.2 |
| Vapor phase cleaning: | | |
| Defluxing | 14.3 | |
| Metal cleaning | 3.6 | |
| "Critical cleaning" | 18.4 | |
| Liquid phase cleaning: | | |
| Open cleaning | 6.6 | |
| Closed systems | 4.2 | |
| Drying | 3.7 | |
| Government | 4.4 | |
| Dry cleaning (total) | | 2.2 |
| Other (total) | | 8.1 |
| Chemical processing: | | |
| Reaction medium | 1.2 | |
| Intermediate | 2.2 | |
| Carrier medium | 2.7 | |
| Cutting fluid | 1.6 | |
| Miscellaneous | 0.4 | |
| Total | | 65.5 |

SOURCE: DuPont (1978a), p. V-5.

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[1] A few million pounds of CFC-11 are used annually in highly specialized solvent applications, which are omitted from this discussion.

## Cleaning and Drying

In cleaning, CFC-113 is used as an industrial solvent to remove flux from printed circuit boards and to clean scientific instruments or metal parts and assemblies.[2] "Critical cleaning" refers to cleaning of plastic and specialty components, many of which are produced in a contamination-controlled environment. For liquid-phase ("cold") cleaning, the solvent is placed in an open or closed tank and the item to be cleaned is dipped in or sprayed with the solvent. For vapor-phase cleaning ("vapor degreasing"), the solvent in the tank is heated to form a vapor zone above the liquid; items to be cleaned may be dipped in the vapor zone as well as dipped in the liquid or sprayed. In both types of cleaning, the solvent coats the item, displacing soils and particulate matter, and then evaporates to leave the item clean and dry.[3]

Drying is a process similar to cleaning, with the solvent used to displace water. Drying equipment units share basic design and functional features with vapor degreasers.

Motives for using CFC-based solvents vary among cleaning applications. Some users have converted to CFC from other solvents, such as trichloroethylene, which are believed to be hazardous to workers. Other users rely on the CFC because it is especially compatible with materials used in the final product, particularly plastics; the use of plastic components in many applications was permitted by the existence of CFC-113, which has been widely available since the early 1960s. Other attractive features of CFC solvent are that it is virtually nontoxic and photochemically nonreactive.

There are dozens of industrial solvents, which include many potential substitutes for CFC in cleaning applications. Among the substitutes most commonly noted are 1,1,1 trichloroethane (also known as methyl chloroform) and methylene chloride. Recently, aqueous cleaners (systems using heated water, sometimes deionized or with detergent additives) have made inroads in the solvent market, particularly for cleaning printed circuit boards. Crude data indicate that CFC-113 accounts for no more than five percent of the current total solvent market,[4] but there may be submarkets in which the CFC is far more important. Industry sources argue, in particular, that CFC-113 is critical to the electronics and aerospace industries and that these industries account for the majority of CFC cleaning sales.

If the cleaning and drying market were to grow in step with projected growth in U.S. electronics production, CFC sales for cleaning and drying applications alone would reach 130 million pounds in 1990. However, regulatory restrictions on other solvents found hazardous to worker health or to the environment could easily double the size of the CFC-113 market. Alternatively, market expansion could be inhibited through increased market penetration by aqueous cleaners or through improved solvent conservation.

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[2] The CFC-based solvent used in these applications may consist of pure CFC-113 or may be a mixture or an azeotropic (constant-boiling) blend of CFC-113 with other solvents, usually methylene chloride. (Even "pure" CFC-113 contains a small amount of other fluorocarbons. One of the two producers markets two grades of pure CFC-113 that differ in the level of other material; both grades are over 99 percent pure.) The composition of an azeotrope affects cleaning strength (usually increasing strength relative to pure CFC-113), odor (the pure CFC is odorless), boiling point, and other solvent characteristics. All data reported in this section exclude the non-CFC components of azeotropes; in 1976, non-CFC components added approximately 7.5 million pounds to solvent sales.

[3] There appears to be some disagreement among industry sources about the amount of CFC-113 used in cold cleaning. However, the total use for vapor and liquid-phase cleaning is not in dispute, and the distinction between the two cleaning methods is not essential in the analysis presented here.

[4] We have no data on solvent usage rates per unit of final product output for any of the industrial solvents. To measure market shares, we assume that a gallon of any solvent will clean the same amount of final output. Then the share of final output cleaned with CFC-113 is given by its share of the total industrial solvent sales in gallons.

## Dry Cleaning

There are currently three main classes of solvents used to dry clean clothing. CFC-113 with detergent additives (under DuPont's trade name Valclene ®) accounts for less than one percent of the market at present. The CFC is mostly used in coin-operated units, where exposure to other solvents is deemed hazardous to the public, and for cleaning specialty goods, such as leathers. The other two classes of dry cleaning agents, petroleum solvents and perchloroethylene, are both under investigation for impending regulation. Regulations on alternative dry cleaning agents could reasonably be expected to expand the market for Valclene much more rapidly than might otherwise be predicted.

## "Other" Uses

In 1976, about three percent of the CFC-113 sold in the United States was used as an inert carrier of ingredients (for example, in paint and coating formulations). A smaller amount was used in mixtures with small amounts of lubricant as a coolant (cutting fluid) in specialized machining. In chemical processing, which was four percent of the 1976 market, the solvent is used in a closed reactor as a medium for chemical reactions or as a raw material for generating other products.

The DuPont report (1978a) rules out substitutes for CFC-113 as an intermediate (raw material) in chemical processing, but notes that, as a carrier or reaction medium, CFC-113 might be replaced by chlorinated solvents, hydrocarbons, or water. However, DuPont argues that the CFC is generally much more costly than the alternatives, suggesting that the CFC is used only where its properties are especially advantageous or essential.

Potential market growth in these applications is uncertain. Both of the CFC-113 producers apply the same projected growth rates to these categories as to cleaning and drying uses (though the two producers do not agree completely on anticipated overall growth rates).

Not shown in Table 3.B.1 is the 2.5 million pounds of CFC-113 used in specialized refrigeration uses. Given the high price of CFC-113 relative to other CFC refrigerants, it is reasonable to presume that this use requires the particular properties of CFC-113 and that there are no feasible substitutes.

The CFC producers do not include refrigerant applications in their solvent market projections. For lack of better information, we assume that this application will grow at the same rates projected for all other applications taken together.

## USE AND EMISSIONS

CFC-113 is the only CFC for which reclamation and reuse are nontrivial at present. If "use" is defined as the amount of CFC used to fill equipment, reclaimed material would be included. In contrast, the data reported below refer to sales of virgin material. Because the amount of CFC emitted cannot be greater than the amount of virgin material produced (regardless of how many times it is recovered and reused), sales is the proper measure for assessing potential emissions.

Projecting future sales of CFC-113 is heavily dependent on knowledge and assumptions about the markets and regulatory prospects for competing solvents, matters largely outside the scope of this study. The importance of uncertainties about future sales (and hence emissions) is illustrated below by means of alternative projections. Later in this section, we use a simulation model of the CFC-113 market to derive the point estimates of CFC-113 use and emissions that appear in the quantitative analysis of policy implications. The details of the simulation model are presented in Appendix E.

### Historical and Projected Solvent Sales

Table 3.B.2 reports data on historical production and domestic nonrefrigerant sales of CFC-113 obtained from its two producers, DuPont and Allied Chemical. Exports are assumed to equal five percent of domestic sales, based on data for 1976. Prior to 1978, imports were negligible.

Table 3.B.2

DOMESTIC PRODUCTION, DOMESTIC AND EXPORT SALES OF CFC-113, 1970 TO 1977

(Millions of pounds)

| Year | Production | Domestic Sales | Export Sales |
|---|---|---|---|
| 1970 | 41 | 39 | 2 |
| 1971 | 42 | 40 | 2 |
| 1972 | 49 | 47 | 2 |
| 1973 | 65 | 62 | 3 |
| 1974 | 69 | 66 | 3 |
| 1975 | 63 | 60 | 3 |
| 1976 | 69 | 66 | 3 |
| 1977 | 81 | 77 | 4 |

SOURCE: Computations performed by Rand from data provided by the two CFC-113 producers, DuPont and Allied Chemical. Refrigerant applications are excluded from all data.

NOTE: Imports of less than 500,000 pounds per year are omitted from domestic sales.

The historical data on production and sales show a sudden drop in 1975, followed by market recovery in 1976. The drop probably reflects the recession in the

U.S. economy in which the electronics industry was especially hard hit. Sales data for other industrial solvents show a similar decline in 1975 and less rapid recovery afterwards.

DuPont and Allied offered somewhat different projections of future domestic market growth. The two sets of estimates were combined to yield the "industry projections" shown in Table 3.B.3.[5] For the first four years, the average annual growth rate for nonrefrigerant sales is higher (eight percent) than for the succeeding years (five percent). These results are similar to those that would be obtained if CFC-113 sales were to grow at the rate projected for electronics industry production.[6] The projections for domestic production assume that exports will continue at five percent of domestic sales and that the import percentage of domestic sales will grow linearly from zero in 1978 to five percent of domestic sales by 1990, the latter percentage having been estimated by industry sources.

Table 3.B.3

INDUSTRY PROJECTIONS OF DOMESTIC PRODUCTION AND SALES OF CFC-113 SOLVENT, 1978 TO 1990

(Millions of pounds)

| Year | Domestic Production | Exports | Imports | Domestic Sales |
|---|---|---|---|---|
| 1978 | 87 | 4 | -- | 83 |
| 1979 | 94 | 4 | -- | 90 |
| 1980 | 101 | 5 | 1 | 97 |
| 1981 | 106 | 5 | 1 | 102 |
| 1982 | 110 | 5 | 2 | 107 |
| 1983 | 116 | 6 | 2 | 112 |
| 1984 | 121 | 6 | 3 | 118 |
| 1985 | 126 | 6 | 4 | 124 |
| 1986 | 132 | 6 | 4 | 130 |
| 1987 | 138 | 7 | 5 | 136 |
| 1988 | 144 | 7 | 6 | 143 |
| 1989 | 151 | 8 | 7 | 150 |
| 1990 | 158 | 8 | 8 | 158 |

SOURCE: Calculated from data supplied by DuPont and Allied Chemical. Refrigeration uses of CFC-113 are omitted.

Industry sources themselves remarked on the uncertainty that currently surrounds prospects for the CFC-113 market.[7] As an illustration of how significant the uncertainties are, Table 3.B.4 lists two hypothetical projections derived from

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[5] The method by which we combined the two sets of projections cannot be described in detail without revealing proprietary information. The general method involved computation of a weighted average of the two projections with greater weight given to the data from DuPont because of its larger CFC-113 market share.

[6] See the Industrial Outlook (1978), Chapter 31.

[7] Those who did not remark on it demonstrated it by their behavior. Throughout this study, it was commonplace to receive contradictory yet equally sincere predictions from different individuals within a company as well as from the same individual in response to questions raised in different contexts.

## Table 3.B.4

### TWO HYPOTHETICAL PROJECTIONS OF DOMESTIC CFC-113 SALES, 1985 TO 1990

(Millions of pounds)

| Year | Lower Projection | Upper Projection |
|---|---|---|
| 1985 | 98 | 284 |
| 1986 | 103 | 298 |
| 1987 | 107 | 311 |
| 1988 | 113 | 327 |
| 1989 | 118 | 344 |
| 1990 | 125 | 362 |

SOURCE: The lower projection reduces the estimate of domestic sales from Table 3.B.3 by 21 percent. The upper projection increases 84 percent of domestic sales by a factor of 2.5 and increases three percent of domestic sales by a factor of 2.0. See text for additional explanation.

alternative speculations about changes in the market environment. The "lower projection" supposes that aqueous cleaners might completely replace CFC-113 in printed circuit board defluxing, which accounts for 21 percent of CFC-113 solvent sales. The "upper projection" assumes that CFC-113 will (a) displace other industrial solvents, doubling its share of that market; and (b) double its dry cleaning market share from one to about two percent.[a] Note that the upper projection could be met only by expanding CFC-113 production facilities beyond the current level of roughly 150 million pounds; such expansion is likely only if current regulatory uncertainty is resolved in favor of permitting rapid growth in the use of CFCs.

### Emissions Processes

In the foregoing data, there is no presumed loss of CFC-113 between production and sales despite producers' estimates that there are production emissions of one to two percent. Our understanding is that the production emissions figures were derived by comparing actual production output with the theoretical output of CFC-113 that should have been achieved given precursor chemical input levels. It is not clear, therefore, whether the production loss consists of CFC-113 rather than the precursor chemicals themselves. In any case, production losses are at most very small.

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[a] As noted earlier, the CFC market share for cleaning and drying has been estimated from the ratio of CFC-113 sales in gallons to total gallons of industrial solvents sold for cleaning applications. Because weights per gallon differ among solvents, a doubling of the CFC market share in gallons corresponds to increasing its use in pounds by a factor of 2.5. For dry cleaning, market share is measured as a fraction of total pounds of clothing cleaned. It is assumed also that both the overall dry cleaning market and the industrial solvent market grow at eight percent per year through 1985 and at five percent per year thereafter.

The producers estimate that about two percent of sales are emitted during packaging and transport to users. The remainder comprises virgin (unreclaimed) solvent deliveries to users.

Following deliveries to users, the emissions process differs somewhat according to application. In cleaning and drying, two types of solvent losses occur:[9] Some solvent escapes in vapor form from the tank or from the surface of items removed from the tank; the rest is removed in liquid form along with contaminants when the tank is emptied for cleaning. The liquid waste may be allowed to evaporate, sealed in drums and buried, or reclaimed and returned to repeat the use cycle. Since the use cycle is repeated ten to forty times per year, it is a good approximation to say that all the virgin input to cleaning and drying use in a given year is either emitted or buried in that same year. There is currently no evidence on whether or when buried waste is emitted; we have derived emissions estimates for an upper bound assuming that all waste is emitted in the year it is buried and a lower bound assuming that the waste is never emitted.[10]

In dry cleaning, the solvent escapes into the atmosphere from residues in cleaned clothing or from equipment filters, which are discarded at frequent intervals.[11] There is no evidence that filters are discarded in any way that would prevent prompt emissions of the CFC. Hence, all dry cleaning emissions are assumed to be prompt.

For all other applications except chemical processing, the DuPont report (1978a) describes the emissions process as being prompt. The closed reactors used in chemical processing may delay emissions, and the CFC-113 that becomes part of another final product may never be released. Our upper-bound emissions estimates treat all chemical processing use as though it is promptly emitted, whereas our lower-bound estimates treat this use as though it is never emitted; actual emissions from this use lie somewhere between these two extremes.

## Historical and Projected Solvent Emissions

Since the upper-bound emissions estimates presume that all CFC-113 domestic sales are promptly emitted, the estimates derive directly from the sales data in Table 3.B.2. To compute the lower-bound case, it is necessary to subtract sales for chemical processing and waste burial from cleaning and drying uses. In the absence of data on CFC-113 chemical processing for years other than 1976, its share of sales for that year is assumed to hold for other years as well. To estimate burial, we developed a simulation of the cleaning and drying emissions process.[12] The simulation model, which also forms the basis for our predictions of policy outcomes, is detailed in Appendix E.

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[9] Many previous studies and some industry sources describe losses as consisting of evaporation, dragout, and disposal. These terms are not used here because they are subject to misinterpretation and are not especially useful in the analysis.

[10] The former case is a true upper bound for all years in which solvent use increases from the year before. For the historical period, this was true except in 1975.

[11] Equipment for dry cleaning is fully enclosed during operation and includes internal reclamation cycles. Opportunities to control emissions further are very limited.

[12] DuPont provided a simulation for a single "typical" vapor degreaser. Our model simulates emissions for eight different categories of cleaning and drying equipment. The model was critiqued by both

According to the simulation model, there were over 11 million pounds of waste generated in 1976, of which some was buried, some was sent to chemical reclaimers, and some was promptly emitted. There are no comprehensive data on the amount of waste sent out for reclamation, but most industry sources presume that reclamation comes to four or five percent of total virgin solvent sales; thus, we assume that no more than three million pounds of waste went to reclaimers in 1976.[13] Of the remaining eight million pounds of waste, perhaps half was buried and half was promptly emitted due to improper disposal practices. The estimated amount of burial is equal to seven percent of virgin solvent sales for cleaning and drying in 1976. The same percentage is applied to data for all years in order to calculate burial.

Table 3.B.5 reports the upper- and lower-bound emissions estimates for the historical period. The upper- and lower-bound emissions projections for 1978 to 1990 are presented in Table 3.B.6. No emissions projections are given for the two hypothetical sales projections from Table 3.B.4 because those merely reflect a sensitivity analysis. However, the same recognition of uncertainties should be applied with respect to Table 3.B.6.

Table 3.B.5

ANNUAL DOMESTIC CFC-113 EMISSIONS, 1970 TO 1977, UPPER- AND LOWER-BOUND ESTIMATES

(Millions of pounds)

| Year | Upper Bound | Lower Bound |
|---|---|---|
| 1970 | 39 | 35 |
| 1971 | 40 | 36 |
| 1972 | 47 | 42 |
| 1973 | 62 | 55 |
| 1974 | 66 | 59 |
| 1975 | 60 | 53 |
| 1976 | 66 | 59 |
| 1977 | 77 | 69 |

SOURCE: Calculations explained in text. The lower-bound projection is equal to 89.12 percent of the upper-bound projection. Refrigeration uses of CFC-113 are omitted.

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of the CFC-113 producers. When combined with data on the characteristics of the equipment stock, the model accounts for over 90 percent of the 1976 CFC-113 use in cleaning and drying. See Appendix E.

[13] A few sources argued that seven to 10 million pounds of reclaimed solvent were used in 1976. These figures are plausible only if reclamation carried out in-house by solvent users is counted. Data in the text refer only to material recycled through outside reclaimers. Material reclaimed in-house is not counted in the data on waste losses.

Table 3.B.6

DOMESTIC CFC-113 EMISSIONS, 1978 TO 1990, UPPER- AND LOWER-BOUND PROJECTIONS
(Millions of pounds)

| Year | Upper Bound | Lower Bound |
|---|---|---|
| 1978 | 83 | 74 |
| 1979 | 90 | 80 |
| 1980 | 97 | 86 |
| 1981 | 102 | 91 |
| 1982 | 107 | 95 |
| 1983 | 112 | 100 |
| 1984 | 118 | 105 |
| 1985 | 124 | 111 |
| 1986 | 130 | 116 |
| 1987 | 136 | 121 |
| 1988 | 143 | 127 |
| 1989 | 150 | 134 |
| 1990 | 158 | 141 |

SOURCE: Upper bound is equal to projected domestic sales from Table 3.B.3. Lower-bound estimate is 89.12 percent of the upper-bound estimate. (See text for additional explanation.) Refrigeration uses of CFC-113 are omitted.

## INDUSTRY AND MARKET CHARACTERISTICS

In other product areas reviewed in this report, there is some bais for measuring the output of the final products manufactured by the use of CFCs. In many instances, there is detailed information on the major firms in th user industry. Because there are several producers of most CFCs, it is usuall reasonable to presume that moderate changes in the amount of use in a productarea would not drastically affect the price at which the CFC is available. Finallythe number of potential substitutes for the CFC in the product area is sufficientlysmall that it is usually possible to analyze in some detail the conditions under wich substitution would occur.

With regard to solvents, none of the foregoing features applie. What follows represents inferences based on limited information available from wide variety of industry sources.[a] Most of the discussion concerns cleaning and drying applications only. Dry cleaning is discussed briefly at the end of is subsection.

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[a] These include the two CFC-113 producers, three manufacturers of cleaning equipment, three chemical reclaimers who reclaim CFC-113, two users in the electronics aerospace industry, a private consultant to the electronics industry, a prominent solvent distributor, and the dry cleaner the International Fabricare Institute.

## The Cleaning and Drying Market

**Producers of CFC-113.** There are two CFC-113 manufacturers, DuPont and Allied Chemical. Each produces CFC-113 in a single plant, the larger of which has sufficient capacity to supply all of the current CFC-113 market. In both plants, CFC-113 is produced jointly with CFC-114, the output of which has fallen dramatically because of the federal regulation of CFC aerosol propellants. Although the production process differs between the two plants, it is clear that the heavy capital investment in each case causes average unit production costs to fall as total output from the plant increases. Since both plants currently have excess capacity because of the CFC-114 restrictions, we presume that current CFC-113 unit production costs are probably above the minimum achievable from the current capital stock. Expansion in the market for CFC-113 might cause prices to fall in real terms, while restriction of the market would probably generate increased real prices.[15] To substantiate an argument that the CFC-113 price would rise if the market were regulated, DuPont gave us a formula relating production costs to market output that assumes a constant supply elasticity of $-0.5$.

CFC-113 sales represent a tiny fraction of total chemical production and revenues for both producers. However, CFC-113 may be more important as a source of current and especially future profits for the two firms, and neither is indifferent to the prospect of regulatory restrictions on this chemical.

The Allied Chemical CFC-113 production facility is located at Baton Rouge, Louisiana, where CFC-11 and CFC-12 are also produced. The DuPont plant is in Corpus Christi, Texas. Both firms gave us highly confidential data indicating that CFC-113 production is a relatively minor source of employment in the Baton Rouge and Corpus Christi communities.

**Distributors.** The CFC-113 is marketed through a few hundred chemical distributors nationwide who usually carry a variety of solvents and actively compete for sales. The same equipment can be used for Allied or DuPont solvent, and users can and do switch among suppliers.

**Equipment Manufacturers.** There are 15 to 20 firms that manufacture cleaning and drying equipment, but the number that market equipment specifically for CFC-113 use is unknown. The two most widely recognized manufacturers of equipment for CFC-113 are Baron-Blakeslee (in Chicago) and Branson (in Shelton, Connecticut); most of the other firms are also located in the Northeast and Midwest. Neither Branson nor Baron-Blakeslee provided data on their employment, but our impression is that there are considerably fewer than 100 full-time-equivalent employees per firm involved in the manufacture of CFC-113 equipment. Both of the well known firms sell a range of equipment types suitable for many different solvents and cleaners.

Table 3.B.7 lists prices estimated by one of the CFC-113 producers for several types of small and medium sized equipment units in a recent year.[16] The prices refer to well designed units available at retail; lower prices would apply to less

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[15] Note that with declining unit costs and only two producers, pricing and output decisions may reflect some degree of oligopoly behavior, with one of the producers acting as a price leader. Hence, prices could be well above marginal cost.

[16] The equipment manufacturers did not provide price data, one arguing that there are so many variations in designs that his price list would be difficult to compile.

## Table 3.B.7

### ESTIMATED COST FOR NEW CLEANING AND DRYING EQUIPMENT, 1976 TO 1977

| Equipment type | Capacity | Features | Purchase Price ($) |
|---|---|---|---|
| Vapor degreaser | Small (15 gal) | Nonultrasonic[a] | 3,000-4,500 |
| | | Ultrasonic[a] | 6,200-7,500 |
| | Medium (80 gal) | Nonultrasonic[a] | 6,200-7,500 |
| | | Ultrasonic[a] | 9,500-11,800 |
| In-house distillation unit | 10 gal/hr | | 2,000 |
| | 80 gal/hr | | 3,000 |
| Dryer | Small (4 gal) | Water-cooled | 8,700 |
| | | Refrigeration-cooled | 10,800 |
| | Medium[b] | Water-cooled | 10,800 |
| | | Refrigeration-cooled | 12,900 |

SOURCE: Estimated by Allied Chemical Company.

[a] Ultrasonic units use sound waves to cavitate the solvent and increase its cleaning effectiveness. The lower price estimates for ultrasonic and nonultrasonic units assume that condensing coils are water-cooled. The higher price assumes direct-expansion refrigerated coils.

[b] Capacity in gallons not reported.

sophisticated units. Other industry sources report that very large units, which make up about 10 percent of the equipment stock, cost upward of $100,000. As the table indicates, the smaller units more generally in use do not represent major investments by the user, especially in comparison to costs for other types of equipment used in electronics and aerospace firms. Furthermore, an industry source estimated that the cost of converting a machine from one solvent to another is modest except for the very large machines. To convert a small degreaser to 1,1,1 trichloroethane, for example, would cost perhaps as much as $2,000.[17]

**Users.** The CFC-113 producers estimate that CFC-113 solvents are used in as many as 5,000 plants nationwide. Presuming that these plants are geographically distributed much like the electronics components manufacturers covered by the *1972 Census of Manufactures*, almost 40 percent are in the Northeast, about 20 percent are in the North Central region, over 10 percent are in the South, and almost 30 percent are in the West; as might be expected, the largest electronics production centers are in California and New York. It is common for a single user firm to have several cleaning or drying units in a given plant and to use several different solvents for different purposes. A solvent distributor offered the following breakdown of the user market: 50 percent of users purchase under 20,000 pounds per year; 45 percent purchase 20,[illegible] pounds to one million pounds per year; five percent purchase over one million pounds per year.

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[17] The changes would primarily involve increasing the temperature at which the vapor zone is formed.

**Reclaimers.** At present, there are five to ten chemical reclamation companies nationwide that reclaim CFC-113. Each of these companies also uses the same distillation equipment to reclaim other chemicals. Consequently, we presume that other chemical reclaimers could enter the CFC-113 market easily without new capital investment.

At present, the price charged for reclaiming CFC-113 to 98 percent or better purity is approximately 30 cents per pound, plus shipping charges. Because shipping charges can add a substantial amount to the cost of reclaimed material, and because until recently virgin solvent cost only 40 to 60 cents per pound, there has been been little incentive for most users to send material to be reclaimed. Instead, the 20 to 40 percent of users who generate enough waste to make reclamation worthwhile often do so by means of in-house stills. The in-house equipment cannot extract as much solvent for reuse as an outside reclaimer could, but in-house reclamation does not involve any shipping costs.[18]

**Disposal.** Liquid waste and the sludge remaining after reclamation must be discarded in some fashion. Some might be properly buried by a disposal company that charges perhaps $10 per drum. Several industry sources are confident that users often either leave the solvent to evaporate from open drums or pay a small fee to someone who will take the drums away, no questions asked.

## The Dry Cleaning Market

Although we do not have detailed data on the costs of using alternative dry cleaning agents, it is clear that CFC-113 is relatively costly. The most commonly used dry cleaning solvent, perchloroethylene, cost about 15 cents per pound in 1976.[19] In the absence of data on Valclene prices in 1976, we presume that it cost about as much as pure CFC-113, 52 cents per pound. Even under an assumption especially favorable to Valclene—that it can clean 2.5 times as much clothing per pound as perc—the cost of using Valclene would be 39 percent higher than the cost of using perc.

The relatively high cost of CFC-113 dry cleaning agents makes it unlikely that the CFC dry cleaning market share will increase much—unless there is regulatory action to restrict the use of other solvents. But because CFC-113 currently holds a small share of the dry cleaning market, even modest restrictions on other solvents could vastly increase the market for CFC-113.

In 1976, approximately three billion pounds of clothing were dry cleaned in the United States. CFC-113 accounted for only about one percent of the market, or 33 million pounds of clothing, while perchloroethylene held about 78 percent of the market, and petroleum solvents held the remaining 21 percent.[20] Limited regulatory restrictions on perc and petroleum solvents could easily double the market for CFC-113, even allowing for the possibility that regulatory action might also reduce the total amount of clothing cleaned. A doubling of the CFC-113 dry cleaning market was assumed in computing the "upper projection" in Table 3.B.4.

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[18] Note that in-house reclamation was not included in the three million pound 1976 reclamation level mentioned earlier in this section. That figure applied only to externally reclaimed waste.

[19] From data published by the U.S. International Trade Association. See the notes to Table 3.B.9 for a full citation.

[20] Data from the International Fabricare Institute.

## OPTIONS TO REDUCE EMISSIONS

Short of reducing final product output, the options for reducing solvent emissions are substitution of other solvents for CFC-113 and improved conservation, which reduces virgin CFC-113 purchases per unit of final output. Every substitute solvent that has come to our attention has some known or suspected risk associated with its use. Some may be hazardous to the health of workers, while others are photochemically reactive and thus might contribute to smog.[21] An assessment of the validity and magnitude of the hazards imposed by non-CFC solvents is beyond the scope of this study, but one will undoubtedly be needed to help EPA judge alternative policies toward CFC-113. In contrast, conservation has few, if any, undesirable health or environmental side effects. However, according to DuPont, improving conservation is an option only in cleaning and drying applications.

One conservation approach involves reducing vapor losses by means of improved equipment designs and better operating practices.[22] Up to a point, vapor losses can be reduced by such techniques as increasing the freeboard height of equipment,[23] using more condensing coils and better refrigerated coils, reducing the speed of item throughput to allow better drainage back into the equipment unit, and covering equipment when it is idle or shut down.[24]

Industry sources frequently mention figures in the range of 60 to 80 percent as the amount of vapor loss conservation achievable with current technology. However, these figures refer to improvements *in poorly designed equipment and in bad operating practices*, which are by no means universal even today. Consequently, the gains to be made from increasing vapor conservation relative to the status quo are much smaller than the industry estimates convey.[25] As an illustration, we computed a hypothetical reduction in vapor losses by using the emissions simulation model mentioned above and reducing all loss rate parameters in the model to the lowest values given to us by various industry sources. The result was a decline in vapor losses from 3,737 pounds per machine per year to 2,039 pounds—a decline of 45 percent. (If reclamation rates remained unchanged, the improvement in vapor losses would reduce cleaning and drying solvent sales by only 36 percent, and total solvent sales by only 30 percent.)[26]

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[21] Even aqueous cleaners have been criticized because they are disposed into waterways, along with the contaminants they pick up during cleaning.

[22] For a detailed list of the standards for equipment designs and operating practices that might be effective, see EPA (1979).

[23] Freeboard is the equipment wall that rises above the solvent surface and condensing coils and helps contain vapors.

[24] The efficacy of carbon adsorption as a means of recovering vapor losses for reuse is debatable. Producers of carbon adsorption units claim that they can recover up to [illegible] percent of vapor losses in solvent applications. One of the CFC-113 producers argues, however, that the exhaust fans that feed the carbon adsorption unit increase vapor losses. Currently, less than one percent of users have carbon adsorption systems, and users and equipment manufacturers who have investigated the systems claim that they are far from economically justified. Technical assessment of this option is required prior to its evaluation as a candidate for mandatory control.

[25] The gains are also smaller than those estimated by EPA (1979), which also estimates emissions effects by comparing conservative equipment with very poorly designed units rather than with the types of units actually in use.

It is evident also that the potential gain from individual conservation improvements is very uncertain.[27] An impressive example concerns the use of covers during shutdown. One industry source who reviewed our preliminary simulation results argued that the vapor loss rate when equipment is shut down is 0.08 pounds per square foot of equipment surface area per hour—and that equipment is always covered during shutdown. Another industry source preferred to assume the shutdown rate is 0.02 when equipment is uncovered and 0.01 when equipment is covered, and that covers are used only three-quarters of the time. If the former assumption is more accurate, average annual shutdown losses are about twice as high, shutdown losses would account for a third of vapor losses or a quarter of total losses—and there would be no opportunity to reduce shutdown losses through increased use of covers.[28]

Similar points can be made regarding the prospective benefit of reclamation as a means of solvent conservation. Like vapor conservation, reclamation means that less virgin solvent is required to perform a given amount of cleaning and drying; hence, potential emissions are less. Some industry sources have speculated that reclamation could replace up to 30 percent of current virgin solvent use. However, our analysis indicates that most of the in-house reclamation that is feasible[29] is already being done and that only 20 percent or so of cleaning and drying solvent losses end up as waste available for external reclamation. Not all of this waste CFC-113 would be reclaimed, since some is too contaminated to warrant reclamation and some cannot be extracted from the waste even with good distillation. Moreover, some waste accumulates slowly from small users, making outside reclamation uneconomical because of the costs of collection and storage. Finally, because reclamation is largely an option only in cleaning and and drying applications, even if as much as 90 percent of the waste could be returned to use, total CFC-113 emissions could be reduced no more than 15 percent.

Solvent substitution, equipment and operating practice improvements, and increased reclamation are options that might be induced by higher CFC-113 prices, as explained in the following discussion of solvent demand. Except for equipment improvements, however, the options are less promising as mandatory control candidates.

Solvent substitution could be caused by banning CFC-113 use, but the desirability of that option depends on how EPA views the risks imposed by other solvents—and there are some current CFC-113 applications where solvent substitution might not be feasible without changing the materials or methods used to produce final products.

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[26] The potential for conservation cited here and elsewhere applies to averages. Certainly, some users could do better; other users, who already practice good conservation, cannot further achieve even the average improvement.

[27] Although there are many published studies that report the emissions effects of various conservation improvements, we have not discovered any documentation reporting results from tests using CFC-113. Given the differences in the chemical properties of different solvents, there is absolutely no technical justification for assuming that the emissions effects estimated from a test using, say, 1,1,1-trichloroethane, would equal those that would be obtained for CFC-113.

[28] The higher shutdown loss assumption also makes the simulation results more nearly account for reported usage of CFC-113 in cleaning and drying in 1978.

[29] Feasibility is determined by the user's requirements for solvent purity relative to the purity achievable from in-house distillation. Using our emissions simulation model, the cost data for stills from Table 3.B.7, and the information that a vapor degreaser can be used as a (crude) still, we have analyzed the economics of in-house distillation. Since it always appears economically justified, we presume it is already being practiced where feasible.

Aside from offering possibly very small emissions improvements, requirements for better operating practices would be virtually unenforceable; even managers at the user sites we visited complained that they cannot be sure that workers are following recommended procedures when not under direct supervision.

Requirements for more reclamation would also be extremely difficult to enforce at the thousands of user sites where CFC waste is generated. Many users might be happy to have a market for their CFC waste because that would solve their disposal problems, but those same users are often reluctant to accept reclaimed material for reuse because it could contain impurities that could damage the products being cleaned.

This leaves equipment standards as the most promising mandatory control candidate, because inspectors could determine whether equipment in use meets the standard, and equipment producers could be required to sell only equipment that meets the standard.[a]

## CFC DEMAND SCHEDULES

Several industry sources have argued vigorously that users of CFC-113 are insensitive to its price, a conclusion with which we disagree. The reasons given to support the sources' contention are: (1) Solvent expenditures are a trivial component of production costs in user industries; (2) although CFC-113 is much more expensive than other solvents, it is used anyway; and (3) the market for CFC-113 has not declined despite rapid price increases in recent years. All three of these observations are accurate, but they do not prove that users are unresponsive to prices of CFC-113.

One user has estimated that solvent expenditures are less than one percent of his production costs, and we suspect that this situation is typical of most cleaning and drying applications. This suggests that solvent prices have little bearing on final product prices and that final product sales would not be affected by solvent price increases of the magnitude contemplated in this study. However, users can reduce CFC purchases without reducing final product output by using more conservative equipment and operating practices, by recycling the CFC, and perhaps by substituting [illegible]ative solvents. Whenever these actions will reduce production costs, the firm has an incentive to undertake them, and firms that respond to such incentives will fare better in their market shares and profits than their less responsive competitors.

The observation that CFC-113 costs more than other solvents when compared gallon-for-gallon or pound-for-pound is accurate, but the more pertinent comparison is overall production costs per unit of final output. Recent information from a confidential source shows that users of 1,1,1 trichloroethane and CFC-113 have similar production costs when measured per square foot of printed circuit boards cleaned. One reason is that CFC-113 requires less energy to form a vapor zone because of its lower boiling point.[39] Another reason might be that CFC loss rates are generally lower. In any case, it is reasonable to expect that competition among solvents would tend to drive the cost of using alternative solvents to equality at the margin, with many inframarginal users finding one or another of the solvents more economical for a particular application.

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[a] Even if the standards were required only for CFC equipment and other solvent equipment continued to be produced, the cost of converting other equipment to CFC use would tend to dissuade users from pursuing that method of evasion.

It is also true that the absolute price of CFC-113 has been rising rapidly, as shown in Table 3.B.8. However, the prices of other solvents have been rising even more rapidly. As indicated by Table 3.B.9, prices of CFC-113 rose 30 percent between 1970 and 1976, whereas the prices of other solvents rose 90 to 117 percent. Since it is changes in relative rather than absolute prices that would influence a user's choice among solvents, the recent history of solvent prices is perfectly consistent with the strong market growth of CFC-113, and does not in any way support the contention that solvent users are unresponsive to prices.

Table 3.B.8

PRICES OF CFC-113, 1970 TO 1977

| Year | CFC-113 Bulk Price (cents per lb) |
|---|---|
| 1970 | 40.0 |
| 1971 | 40.0 |
| 1972 | 40.0 |
| 1973 | 38.4 |
| 1974 | 43.3 |
| 1975 | 48.5 |
| 1976 | 52.0 |
| 1977 | 56.0 |

SOURCE: Prices reported by DuPont.

Our model of CFC-113 demand presumes that there is some price responsiveness by users. We expect the use of CFC-113 to be less at higher prices in part because higher CFC prices make investment in more efficient equipment cost-saving for the firm and in part because higher CFC prices would begin to outweigh the perceived disadvantages of reclaimed CFC, at least for some users. We also expect some users of CFC-113 to convert to an alternative solvent if the CFC price rises sufficiently; this view is consistent with the fact that some users converted to CFC-113 from an alternative solvent in the past (for reasons of economics, advantages of the CFC solvent in certain applications, and regulatory action toward other solvents).

Unfortunately, neither of the CFC-113 producers provided information from

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[39] One source estimates energy use for a [illegible] gallon, one-sump vapor degreaser to be 8 to 11 kilowatts, depending upon operating conditions. Overall, energy consumption would be 30 to 40 percent less with CFC-113 than with such alternative solvents as methylene chloride, trichloroethylene, and 1,1,1-trichloroethane.

## Table 3.B.9

### COMPARISONS OF PRICE INDEXES FOR CFC-113 AND OTHER CHEMICALS

(1970 = 100)

| Year | Industrial Chemicals[a] | Methylene Chloride[b] | 1,1,1 Trichloro-ethane[b] | Trichloro-ethylene[b] | Perchloro-ethylene[b] | CFC-113[c] |
|---|---|---|---|---|---|---|
| 1970 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1971 | 101 | 88 | 90 | 100 | 100 | 100 |
| 1972 | 100 | 88 | 90 | 100 | 86 | 100 |
| 1973 | 102 | 100 | 90 | 100 | 86 | 96 |
| 1974 | 150 | 163 | 130 | 157 | 143 | 108 |
| 1975 | 205 | 200 | 170 | 214 | 200 | 121 |
| 1976 | 217 | 213 | 190 | 214 | 214 | 130 |

[a] Computations based on *Handbook of Labor Statistics 1977*, Table 118, p. 261.

[b] Computations based on U.S. International Trade Commission (1976); prices in this source are determined by dividing the value of sales by quantity where value of sales is F.O.B. (if available) or delivered price.

[c] Computations based on bulk prices as reported in Table 3.B.8.

their own marketing studies or experience that would allow us to discern which solvent applications would be most susceptible to solvent substitution or the conditions under which such substitution would occur.[32] Given the large number of alternative solvents and the wide range of solvent applications, it is beyond the resources of this study to conduct such an analysis. Therefore, our model of the opportunities for solvent substitution is very cautious, and may well understate the degree of solvent conversion that might be induced by higher prices for CFC-113. If so, our models would: (a) understate the elasticity of CFC-113 demand; (b) understate the degree of emissions reduction under an economic incentives policy; and (c) overstate the costs to users of such a policy. This tendency toward caution is consistent with assumptions elsewhere in this study, as explained in Secs. I and II.

Our analysis of CFC-113 demand focuses on cleaning and drying applications where we have at least some crude evidence on the costs and effectiveness of various options to reduce emissions. The analysis presumes that final product output in this application category is unaffected by CFC prices and that the CFC users will use reclaimed CFC and invest in solvent conserving equipment when it is cost-saving to do so. Because the share of cleaning and drying use that is amenable to solvent substitution is uncertain, we develop a demand scenario that is cautious about the likelihood and degree of substitution. We assume, first, that there is a cost of converting equipment that must be outweighed by CFC price increases before conversion will occur. Second, we assume that the cost of using an alternative solvent is equal to the current cost of using CFC-113 only for the marginal user, but is higher for inframarginal users.[33] Aside from the substitution assumptions, the demand model has several other features.

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[32] When there are only two producers of a chemical, it is understandable that each of them would be reluctant to provide detailed marketing data or studies that, if revealed here, would convey proprietary information to the competitor.

First, the model assumes that the use of reclaimed material would increase if the price of virgin CFC-113 reached $1.00 per pound (in 1976 dollars). The cost of reclamation processing is not affected by the price of virgin material, and ease of entry into CFC reclamation suggests that this activity could increase without changing processing costs. At $1.00 per pound of virgin CFC, many users would find the difference between reclaimed and virgin prices sufficient to compensate for increased risk of impurities and higher transport and handling costs for reclaimed material. Whereas the average share of waste reclaimed in 1976 was only 20 percent, we presume that the share could rise as high as 75 percent, with some users more heavily engaged in this activity than others.

Second, the demand analysis uses the emissions simulation model mentioned earlier (and detailed in Appendix E) to evaluate the effect of conservation improvements on solvent losses for each of eight cases describing different equipment sizes and use characteristics. Table 3.B.10 describes the eight cases and lists the prices we assume for conservative equipment in each case.

We do not have data on equipment prices for less conservative units, so we

Table 3.B.10

ASSUMPTIONS FOR CLEANING AND DRYING CFC-113 DEMAND SIMULATIONS

| Case Number | Case Description | Number of Machines in 1976 | Price of Conserving Equipment (1976 $) | Annual Vapor Loss Reduction (lb) |
|---|---|---|---|---|
| 1 | Spray unit | 1,760 | 3,300 | 1,084 |
| 2 | Small, one-sump | 3,520 | 5,300 | 1,108 |
| 3 | Small, two-sump | 3,520 | 7,800 | 1,228 |
| 4 | Medium, one-sump | 440 | 7,500 | 3,225 |
| 5 | Medium, two-sump | 990 | 10,000 | 4,280 |
| 6 | Medium, conveyor | 440 | 12,500 | 1,161 |
| 7 | Large, one- or two-sump | 110 | 78,000 | 12,891 |
| 8 | Large, conveyor | 220 | 125,000 | 4,355 |

SOURCE: Emissions simulation model developed for this study, plus cost data from Table 3.B.7.

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[33] We derive the degree of substitution of alternative solvents from the following formula, where $E_c$ is the new annual expenditure for CFC after its price increases, $C_0$ and $E_0$ are current use and expenditures for CFC, K is the annualized cost of investment to modify equipment for a different solvent, and $C^*$ is the level of CFC use after substitution at the new CFC expenditure level: $C^*/C_0 = E_0/(E_c - K)$. $E_0$ and $E_c$ include the annualized cost of investments in equipment. The value of K is estimated to be 40 percent of the cost of new equipment (based on data from an industry source), except for conveyorized machines where K is assumed to be somewhat less than 40 percent of total equipment costs.

examined the outcomes of an investment decision model[34] in which the conservative equipment alternatively costs 20, 30, or 40 percent more than less conservative units. Using the 20 and 30 percent parameters, we find that virtually all users would choose the more conservative equipment at virgin CFC prices much below the 1976 level of 52 cents. With the 40 percent parameter, users in simulation cases 1, 2, 4, and 5 would all choose the more conservative equipment when making a new investment decision at a CFC price of 50 cents or less. The 40 percent parameter is used in the results reported here because it is cautious—i.e., it yields a lower estimate of demand elasticity than the alternative parameters.

The estimates of reductions in vapor losses from more conservative equipment derive from detailed assumptions about underlying loss rate parameters for different types of machines. The estimated reductions in vapor losses from making conveyorized machines more conservative are smaller than the estimated reductions for nonconveyorized equipment of a similar size; conveyorized machines are enclosed and therefore have lower vapor loss rates than nonconveyorized machines, so the gains that can be achieved from improved equipment design are smaller for conveyorized units.

Finally, the demand scenario assumes that increases over time in final output produced with CFC-113 are accomplished through proportional growth in the size of the equipment stock, leaving its distribution among the eight simulation cases unchanged. If this had been true historically, nearly 60 percent of the 1976 equipment stock would have been at least six years old in 1976. For the results shown here, we assume that all of the equipment of that vintage will be replaced in 1980, but the results would not be greatly affected if a somewhat longer life (up to about 15 years) were assumed. Similarly, the remainder of the 1976 stock (whose average age in 1976 was about three years) is assumed to be due for replacement on its tenth anniversary, but would be replaced earlier if early investment in more conservative equipment is justified by reduced production costs.[35] It turns out that all existing equipment in cases 1, 2, 4, and 5 would be replaced with more conservative units in 1980 if the CFC-113 price reached 60 cents.

If the relative price of CFC-113 were constant over time, we would expect the share of final product made using the CFC to remain constant as well. Using electronics industry growth as a proxy for growth in all cleaning and drying applications, the CFC-using equipment stock would have grown about 10 percent in 1977 and at eight percent per year in 1978, 1979, and 1980. We would predict (along with industry sources) that the growth in solvents-using industries, and thus the CFC equipment stock, would be eight percent in 1981, then five percent per year thereafter, through 1990.

However, the price of CFC-113 has not remained constant in real terms since 1976. Recent data from DuPont indicate that the 1980 price of CFC-113 is 38 percent above the 1976 price, whereas prices of CFC-11 and CFC-12 rose 20 percent or less over the same four-year period. Before obtaining these data, we based our model calculations on the assumption that the 1980 CFC-113 price would be 60 cents in real terms, which is only one or two cents below the estimate we would have obtained from the more recent data.

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[34] The investment model assumes that users amortize the equipment over eight years and discount solvent savings at 20 percent per year.

[35] It is possible that users would modify rather than replace existing units in order to improve conservation. The assumption that equipment is replaced after ten years even though the functional lifetimes of units might be 20 years is intended to compensate for what might be an overestimate of the costs of improving conservation in existing equipment.

The market supply formula given us by DuPont indicates that future relative CFC-113 prices will not remain constant. As noted earlier, the supply elasticity is −0.5, implying that CFC production prices would fall (relative to other chemicals) by one-half percent for each one percent increase in output levels. Our analysis assumes that CFC-113 prices will fall according to that rule, at least until total market output of the CFC approaches the current capacity constraint of about 150 million pounds. For total industry production of 140 million pounds or more, we assume that the relative CFC price would "bottom out" at about 40 cents per pound (in 1976 dollars).

In the 1990 baseline demand analysis, the CFC-113 price decline would encourage firms that would have chosen other solvents to choose CFC-113 instead. Assuming that the capital costs for converting from another solvent to CFC-113 are the same as the costs of converting from CFC-113 to another solvent, use of the CFC in 1990 would be augmented by 16.0 million pounds because of solvent conversion by users in cases 4, 5, and 6 combined. The CFC-113 price would be 40 cents in 1990, with total use amounting to 147 million pounds.

Table 3.B.11 reports the results from the demand scenario. For lack of better information, the estimates of CFC sales for all applications other than cleaning and drying assume that those uses are unresponsive to prices and will grow at the same annual rates as final product output from the cleaning and drying applications. The total demand values for virgin CFC prices of 60 cents in 1980 and 40 cents in 1990 are those we predict in the absence of policy action. Although the use projections include refrigeration applications of CFC-113, the baseline total demand values fall short of the industry projections of 1980 and 1990 sales for solvent-related applications. The principal reason is that our models predict that the equipment stock will become more conservative in the near future (even in the absence of policy action), while the CFC-113 share of the final product market remains constant. Industry sources were not specific about the assumptions underlying their projections, but one source commented that his growth rates, which were lower than others, presumed there would be improved conservation.

In results not reported here, we also calculated a demand scenario that assumes that there are no opportunities for solvent substitution. The demand results in the two scenarios diverge as the CFC-113 price increases because the reported scenario specifies that more users will find solvent substitution cost-effective as the CFC-113 price rises relative to the prices of other solvents.

The reported scenario is somewhat closer to the industry projection of 1990 sales than is the nonsubstitution scenario, and also embodies the plausible assumption that solvent users have some opportunities for substituting among solvents when economic conditions change. The reported scenario is the basis for the baseline use and emissions projections and for the policy analyses throughout the rest of this report. Our estimates might even understate the degree of emissions reductions achievable from increased CFC-113 prices; this cautiousness in our analysis reflects the especially limited data availability for this product area.

Table 3.B.11

CFC-113 Demand Schedules, 1980 and 1990

(Millions of pounds)

| Bulk Price of Virgin CFC-113 (1976 $) | Cleaning and Drying | | | | | |
|---|---|---|---|---|---|---|
| | Small Units | Medium Units | Large Units | Total | All Other Applications | Total |
| | | | 1980 | | | |
| 0.60 | 24.8 | 15.2 | 14.1 | 54.1 | 24.2 | 78.3 |
| 0.80 | 18.8 | 14.7 | 14.1 | 47.6 | 24.2 | 71.8 |
| 1.00 | 11.6 | 11.1 | 11.4 | 34.1 | 24.2 | 58.3 |
| 1.25 | 10.7 | 9.0 | 9.8 | 29.5 | 24.2 | 53.7 |
| 2.00 | 8.5 | 6.3 | 6.6 | 21.4 | 24.2 | 45.6 |
| 2.80 | 6.9 | 4.7 | 5.2 | 16.8 | 24.2 | 41.0 |
| | | | 1990 | | | |
| 0.40 | 41.6 | 40.8 | 23.7 | 106.1 | 40.6 | 146.7 |
| 0.60 | 31.5 | 25.4 | 23.7 | 80.6 | 40.6 | 121.2 |
| 0.80 | 31.5 | 24.6 | 23.7 | 79.8 | 40.6 | 120.4 |
| 1.00 | 19.6 | 18.6 | 19.1 | 57.2 | 40.6 | 97.8 |
| 1.25 | 17.9 | 15.0 | 16.4 | 49.3 | 40.6 | 90.0 |
| 2.00 | 13.4 | 10.5 | 11.0 | 34.9 | 40.6 | 75.6 |
| 2.80 | 10.6 | 7.9 | 8.7 | 27.2 | 40.6 | 67.8 |

SOURCE: Calculations from simulation models described in text. Scenario assumes that users can substitute among solvents. Components may not sum to totals because of rounding.

## MANDATORY CONTROL CANDIDATES

For reasons given earlier, the only mandatory control candidate considered here is equipment standards. A standard applied only to new equipment promises to be far less effective than standards requiring improvements in existing equipent as well. We expect that most existing equipment is due for replacement by 1983, so new source standards would differ little from retrofit if current replacement schedules are followed. However, new source standards might encourage users to retain the older and less conservative equipment longer, making new source controls less effective over the decade. Our mandatory controls analysis presumes that the controls would require improving existing as well as new equipment.

There are two regulatory options for retrofit controls that might be considered. One is to impose the same equipment standards for all solvents. This regulation would impose nearly the same equipment costs and yield similar reductions in emissions for all solvents. The outcome of this regulation would be the same regardless of whether users can substitute among solvents, because the policy would not much affect the relative costs of using alternative solvents.[36] The policy would not dissuade users from substituting CFC-113 for other solvents, and thus would be less effective in restricting CFC use than would a policy directed only at CFC use. In contrast, it appears that a regulation only on CFC-113 use could dissuade some users of other solvents from converting to the CFC as its price declines over time, and thus would reduce CFC emissions more than regulations applied to all solvents might. Our analysis assumes controls would apply only to CFC-113, since regulation of other solvents is outside the scope of this study.

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[36] Mandatory controls, if perfectly enforced, would raise the average conservation improvement in all cases by eliminating below-average uses in each case. The analysis assumes that enforcement would not be perfect.

Under equipment standards, users in cases 3, 6, 7, and 8 who would not otherwise improve their conservation would be required to do so, thus reducing total CFC use by the year 1990. The reduction in use would keep the CFC-113 price from falling as much as it would in the absence of regulatory action. Consequently, there would be less incentive for users of other solvents to convert to CFC-113 as its price declines.

If we assume that mandatory controls would dissuade users from converting to CFC-113 in cases 4 and 5, then 1990 use under mandatory controls would come to 120.9 million pounds and the supply price of the CFC would be about 45 cents. This price is very close to the estimated price at which solvent substitution in cases 4 and 5 would occur—so close that a small change in the data used in the analysis would shift the balance of the predicted outcomes.[37] Our analysis gives the benefit of the doubt to the mandatory controls, assuming that they will dissuade solvent users from converting to CFC-113 in cases 4 and 5. Because the users in these two cases who might consider solvent substitution are very close to indifferent about it at a CFC price of 45 cents, the compliance costs associated with dissuading conversion are very small.

Table 3.B.12 summarizes the estimated outcomes of a mandatory control policy that requires retrofit equipment standards, but only for equipment in which CFC-113 is used. Appendix E uses case 3 in the simulation model to illustrate how the results reported in Table 3.B.12 were obtained.

## CONCLUSIONS

Before this study, solvent applications were regarded as a minor source of CFC emissions. Our results prove otherwise. Currently, CFC-113 accounts for over 15 percent of CFC emissions (measured in permit pounds). In the absence of policy action, CFC-113 could account for almost 20 percent of such emissions by 1990.

Previous analyses of solvent emissions controls use test results for non-CFC solvents and compare good and bad equipment designs without investigating the characteristics of equipment actually in use. As a result, those studies suggest that the ability to reduce solvent emissions through mandatory controls is far greater than our analysis predicts. Nevertheless, mandatory controls on equipment standards in CFC solvent applications would be an important contributor to the emissions reductions achievable from the benchmark mandatory controls examined in this study.

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[37] The 45 cent price would not dissuade users from converting in case 6.

## Table 3.B.12

## EMISSIONS REDUCTIONS AND COMPLIANCE COSTS UNDER MANDATORY EQUIPMENT STANDARDS

| Case Number | Numbers of Machines Affected[a] |  | 1980 Outcomes |  | 1990 Outcomes |  | Cumulative Outcomes |  |
|---|---|---|---|---|---|---|---|---|
|  | 1980 | 1990 | Emissions Reduction (millions of lb) | Compliance Costs ($ millions) | Emissions Reduction (millions of lb) | Compliance Costs ($ millions) | Emissions Reduction (millions of lb) | Compliance Costs[b] ($ millions) |
| 3 | 4,878 | 8,173 | 6.0 | 0.4 | 10.0 | 2.6 | 86.4 | 6.6 |
| 4[c] | -- | 631 | -- | -- | 3.1 | 0.2 | 7.1 | 0.1 |
| 5[c] | -- | 1,325 | -- | -- | 7.5 | 0.4 | 15.5 | 0.3 |
| 6[c] | 610 | 1,639 | 0.7 | 0.3 | 6.3 | 1.0 | 29.2 | 3.3 |
| 7 | 152 | 255 | 2.0 | 0.7 | 3.3 | 1.8 | 28.3 | 7.2 |
| 8 | 305 | 510 | 1.3 | 3.2 | 2.2 | 5.8 | 19.2 | 28.2 |
| Total | 5,945 | 12,533 | 10.0 | 4.5 | 32.5 | 11.6 | 185.7 | 45.7 |

SOURCE: Calculations based on a simulation model described in Appendix E. Components may not sum to totals because of rounding.

[a] The number of machines affected in 1990 includes machines affected in all prior years and still in operation.

[b] Sum of annual compliance costs, discounted at 11 percent per year. The average annual compliance cost per pound of emissions reduction is \$0.15 in case 3; \$0.05 in case 4; \$0.05 in case 5; \$0.21 in case 6; \$0.45 in case 7; \$2.49 in case 8; \$0.43 overall.

[c] Includes effects of controls on dissuading substitution of CFC-113 for other solvents as the CFC-113 price falls. (See text.) In each case where there is no such effect in 1980, but only in later years, the cumulative costs and emissions estimates use a constant average rate of annual change based on the assumption that the 1980 value is 10,000 pounds, or 500 dollars.

Increasing the CFC-113 price could achieve even greater emissions improvements, assuming that users are able to substitute among alternative solvents. As indicated above, we believe that these demand estimates are more likely than not to understate the elasticity of CFC-113 demand, and thus might cause us to overstate the probable costs to CFC users of each of the economic incentives policy designs under consideration.

Solvent substitution is not, of course, a panacea. Other solvents appear to impose their own health and environmental hazards, and require some increase in energy utilization. The potential effectiveness and the desirability of using policy to induce substitution among solvents cannot be determined in this study, and remain important issues for further investigation by EPA.

# III.C. RIGID POLYURETHANE AND NONURETHANE FOAMS

## INTRODUCTION

Since the early 1960s, CFCs have been increasingly used as a blowing agent in closed cell plastic foams. By 1976 closed cell plastic foams accounted for 17 percent of all nonaerosol CFC use. Figure 3.C.1 presents a schematic of the major types and applications of closed cell foams. Although these products are characterized by an extremely diverse and growing number of applications, two general types of CFC blown closed cell foams can be identified: rigid polyurethane and isocyanurate foams, and nonurethane foams.[1]

### Rigid Polyurethane and Isocyanurate Foams

Rigid urethanes and isocyanurates are the largest closed cell foam consumers of CFCs. By far the most extensive use of these plastic foams is as an insulation material in construction, refrigeration, and transportation applications. In fact, CFC blown rigid urethane and isocyanurate foam is the most effective insulation medium, in terms of thermal efficiency, available on the market today. As a consequence of rising energy prices, the use of these materials in the economy is growing very rapidly and will continue to do so in the absence of regulation.

Insulating foams are widely used in sheathing and roofing applications in commercial buildings. The foam insulation residential sheathing market was virtually nonexistent as late as 1972, but is currently expanding at a dramatic rate at the expense of the market shares of wood fiberboard and other sheathing materials. Industrial construction insulation applications are dominated by the use of rigid urethanes that are sprayed on industrial pipes and storage tanks.[2] Rigid urethane foam is now the most prevalent insulation in the wall cavities of home refrigerators and freezers, and its use in commercial refrigeration units, almost nonexistent a decade ago, is growing rapidly.[3] Finally, urethane insulation is foamed within the walls of refrigerated truck trailers and railroad freight cars to reduce the energy costs of cooling their payload.

In addition to providing the highest possible level of thermal efficiency, rigid urethane foams provide structural strength, reduce weight, and increase interior storage capacity (by reducing wall thickness) in several end-use applications. One

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[1] The classification of a plastic foam as "open" or "closed" celled is not always obvious. In fact, some nonurethane foam products contain a significant fraction of open cells. The term "closed" cell foam is used as a convenient label for the class of foams considered in this section, rather than as a technical description of a foam product's characteristics.

[2] Note that foam building materials, such as rigid urethane sheathing, that are installed at an industrial site are classified in the commercial construction market. In contrast, rigid urethanes classified in the industrial construction market are generally "foamed" at the job site, rather than being centrally produced.

[3] A home refrigeration appliance contains as much as three to six times more CFC blowing agent in its walls than CFC refrigerant in its cooling system.

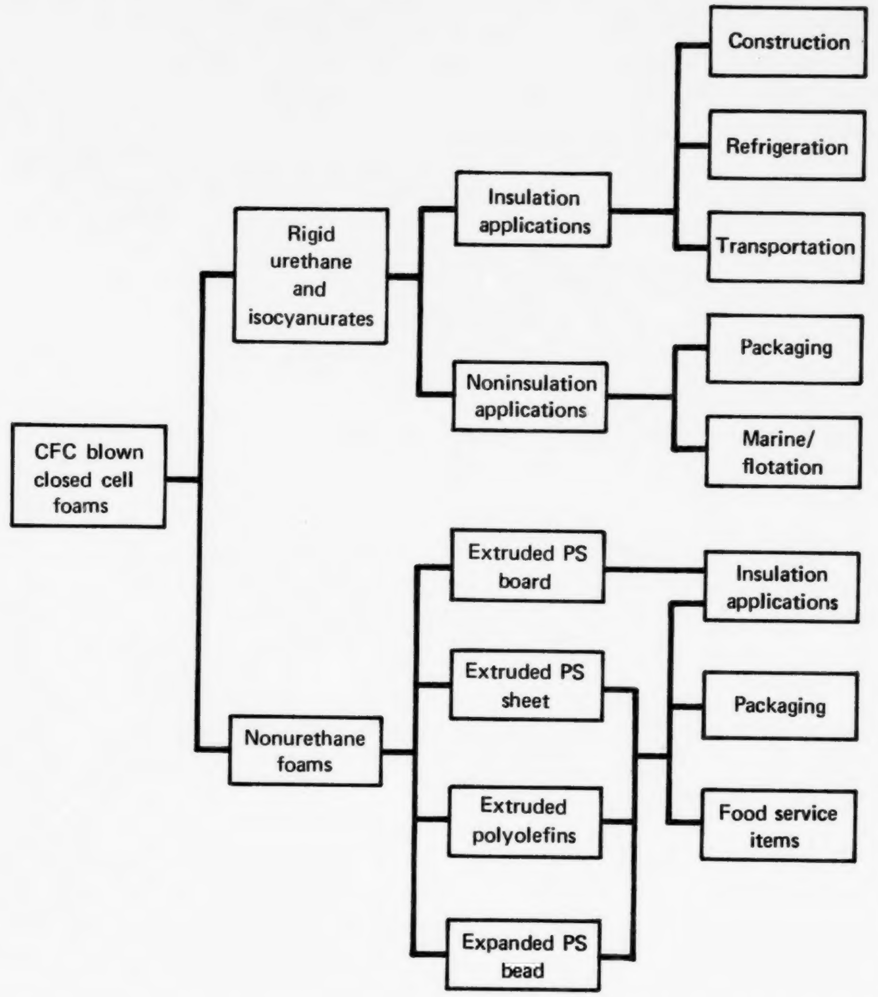

Fig. 3.C.1—Major types and applications of CFC blown closed cell foams

or more of these advantages is observed in home refrigerators and other refrigeration products, in some construction applications, and in refrigerated truck trailers.

Noninsulating uses of rigid urethane foam are far less important in terms of both foam output and CFC consumption. Packaging applications involve foaming rigid urethane around delicate, often expensive, items to be transported. Marine and flotation applications include foaming rigid urethane in boat hulls for structural strength and safety purposes, as well as the production of foam logs, which serve as waterborn cushions and buoys.[4]

Finally, a relatively recent application of CFC blown rigid urethane is reaction injection molding (RIM), a process for fabricating high density polyurethane foam parts. The RIM process is increasingly being used to fabricate automobile parts, but currently consumes only small quantities of CFCs.[5]

Virtually all CFC blown rigid urethane and isocyanurate foams employ CFC-11 as a blowing agent.[6] In addition to acting as a blowing agent in the production process, CFC-11 plays a particularly important role in insulating foams. Indeed, the superior insulating properties of these products is due solely to the presence of CFC-11 in the foam cells. Because of the very low thermal conductivity of this blowing agent, CFC blown insulations are approximately twice as efficient as equally thick nonfoam alternatives, in terms of the amount of heat transfer permitted. While urethane foams can be produced without CFC-11 by reacting isocyanates with water to produce a carbon dioxide blowing agent, the carbon dioxide blown foam retains only the structural properties of its CFC blown counterpart, and the relative thermal efficiency of the foam product is completely lost.[7]

### Nonurethane Foams

Like the rigid urethanes, CFC blown nonurethane foams, which are dominated by the polystyrenes and extruded polyolefins, are employed in a wide variety of applications. There are three basic types of polystyrene foams—extruded polystyrene (PS) board, extruded polystyrene sheet, and expanded polystyrene. Dow Chemical first introduced extruded PS board under the trade name Styrofoam during World War II. Extruded PS board is primarily used as an insulating material in building construction. Due to its use of CFC-12 as a blowing agent, this product has desirable thermal properties (which are exceeded only by rigid urethane) and has the additional advantage of being highly resistant to moisture penetration.

Extruded PS sheet and film represents the largest consumer of CFCs among the nonurethane foams. First introduced in the mid-1960s, these foams were originally blown with pentane, but in part because of the fire hazard associated with this agent, a conversion to CFC-12 began in about 1967. Polystyrene sheet products are also used in some insulation products, but their primary application is as a packaging material. The major markets for these foams are in stock foam trays for meat, poultry, and produce products, foamed egg cartons, and "single service" food containers for the rapidly growing fast-food and institutional food industries. Miscellaneous uses for PS sheet include drinking cups, although this market is dominated by expanded PS foams, and labels for glass bottles, a rapidly growing foam market.

Expanded PS foam products account for virtually all of the foam drinking cup market and are fabricated into a variety of other products including packaging materials, insulation board, ice chests, and flotation products. Although expanded PS foams constitute the largest polystyrene market in terms of foam output, the market penetration of CFC blowing agents in these foams is quite low. Consequently, very little CFC is used in the manufacture of these products and they are not dealt with extensively in this analysis.

The output and CFC use of the other nonurethane foams is only a small fraction of that of the polystyrenes. These products include the extruded polyolefins (polyethylene and polypropylene), phenolics and polyvinyl chloride foams. The largest of these minor categories is polyolefin, which is used as an insulating material in electric cables, as well as in packaging, gasketing and sealing, marine products, flexible foam insulation, and expansion joints in building construction.

The nonurethane foams employ a variety of CFC blowing agents. Although the primary blowing agent for PS board is methyl chloride,[8] CFC-12 is used to reduce the warping of the finished board product and, as noted above, to provide thermal integrity. The most widely used blowing agent in extruded sheet is CFC-12. According to the DuPont report (1978a), the polyolefins and other minor foam categories use CFC-11, CFC-12, CFC-114, and small quantities of CFC-113 and CFC-115. Available evidence indicates that overall CFC-12 accounts for about 90 percent of all the CFC blowing agents used in nonurethane foams.

A substantial portion of all extruded PS sheet is currently produced with pentane blowing agents. However, the market share of pentane blown extruded sheet has eroded rapidly in recent years, from 45 to 50 percent in 1973[9] to about 35 percent in 1977. The use of pentane in extruded sheet poses a serious fire hazard. In fact, at least three foam plants that produced pentane blown foam reportedly have been destroyed by fire.[10] Chlorofluorocarbons are nonflammable, and substantial increases in tooling and insurance costs would accompany any conversion from CFC to pentane. According to DuPont, while several producers of polystyrene sheet have switched from pentane to CFC, there have been no instances of producers substituting pentane for CFC blowing agents.[11]

## CFC USE AND EMISSIONS

Table 3.C.1 presents rigid urethane foam production data for aggregated product categories. The production of CFC blown rigid urethane foam is substantial, amounting to about 489 million pounds in 1979. Under the impetus of high energy prices, production is expected to grow dramatically through 1982. After 1982, annual growth rates are expected to decline as foam markets become relatively saturated. Expected production in 1990 is 1.2 billion pounds. Over 90 percent of this foam output is in the three major insulation markets: construction, refrigeration, and transportation.

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[4] High density rigid urethanes are fabricated into structural and decorative furniture parts. However, these high density foams are not CFC blown and involve different producers and technical production processes than CFC blown foams. As a result, furniture applications are not considered in this report.

[5] While the use of the RIM process is growing rapidly, in 1978 this application consumed only about one million pounds of CFC-11. Consequently, even if CFC use in the RIM process grows faster than in any other application examined in this report, total use in 1990 would be at relatively small levels.

[6] As discussed below, some production processes also employ modest amounts of CFC-12.

[7] CFC blown urethane insulation has a k-factor (a measure of thermal conductivity) of 0.11 to 0.16, depending upon the physical characteristics of the foam and its environment. In contrast, the k-factor of fiberglass or carbon dioxide blown foam is roughly twice as high, 0.24 to 0.29. (DuPont, 1978a, p. IV-12.) In other words, non-CFC blown insulation will transfer about twice as much heat as CFC blown foam per unit of thickness.

[8] Methyl chloride should not be confused with methylene chloride, which is used in solvent applications and as an auxiliary blowing agent for flexible urethane foams.

[9] Arthur D. Little Inc. (1975), p. IV-79, and Midwest Research Institute (1976a), p. 123.

[10] DuPont (1978a), p. 14; and Allied Chemical (1977), p. 18.

[11] Industry sources also list methylene chloride as a potential substitute for CFC in some polypropylene foams, although this research is still in the preliminary stages.

### Table 3.C.1

### RIGID POLYURETHANE AND ISOCYANURATE FOAM PRODUCTION, 1960 TO 1990

(Millions of pounds)

| | Insulation | | | | | | |
|---|---|---|---|---|---|---|---|
| Year | Construction[a] | Refrigeration | Transportation | Total | Packaging | Marine/ Flotation | Total CFC Blown |
| | | | Historical | | | | |
| 1960 | 1.0 | 4.0 | 4.0 | 9.0 | -- | 1.0 | 10 |
| ... | | | | | | | |
| 1965 | 20.0 | 19.0 | 14.8 | 53.8 | 1.0 | 4.6 | 59 |
| ... | | | | | | | |
| 1970 | 78.3 | 51.2 | 29.8 | 159.3 | 7.2 | 15.9 | 182 |
| 1971 | 85.5 | 57.8 | 29.1 | 172.4 | 6.0 | 11.2 | 190 |
| 1972 | 109.5 | 63.4 | 37.2 | 210.1 | 7.0 | 14.4 | 232 |
| 1973 | 137.0 | 72.3 | 51.3 | 260.6 | 9.1 | 15.4 | 285 |
| 1974 | 145.1 | 74.8 | 49.5 | 269.4 | 12.1 | 13.8 | 295 |
| 1975 | 166.2 | 72.6 | 48.4 | 287.2 | 13.2 | 13.2 | 314 |
| 1976 | 162.0 | 60.0 | 40.0 | 262.0 | 16.0 | 14.0 | 292 |
| 1977 | 199.0 | 70.0 | 42.0 | 311.0 | 18.0 | 14.0 | 343 |
| | | | Projected | | | | |
| 1978 | 247.4 | 80.2 | 43.0 | 370.6 | 20.0 | 15.0 | 406 |
| 1979 | 312.2 | 92.3 | 45.0 | 449.5 | 23.0 | 16.0 | 489 |
| 1980 | 370.1 | 107.1 | 47.0 | 477.2 | 26.0 | 17.0 | 567 |
| 1981 | 435.4 | 125.1 | 48.0 | 608.5 | 28.0 | 18.0 | 655 |
| 1982 | 505.0 | 147.0 | 50.0 | 702.0 | 30.0 | 19.0 | 751 |
| 1983 | 543.0 | 150.7 | 51.8 | 745.5 | 32.0 | 20.0 | 798 |
| 1984 | 583.5 | 154.0 | 53.6 | 791.1 | 34.0 | 22.0 | 847 |
| 1985 | 627.4 | 158.3 | 55.4 | 841.1 | 36.0 | 23.0 | 900 |
| 1986 | 674.5 | 161.1 | 57.4 | 893.0 | 38.0 | 24.0 | 955 |
| 1987 | 725.1 | 166.6 | 59.4 | 951.1 | 41.0 | 26.0 | 1,018 |
| 1988 | 779.6 | 173.6 | 61.5 | 1,014.7 | 44.0 | 27.0 | 1,086 |
| 1989 | 838.1 | 181.2 | 63.6 | 1,082.9 | 47.0 | 29.0 | 1,159 |
| 1990 | 901.0 | 181.4 | 65.8 | 1,148.2 | 50.0 | 31.0 | 1,229 |

SOURCES: Historical data based on Bedoit (1974), and Midwest Research Institute (1976a). Projections based on information from Mobay Chemical Corporation (1978), Olin Chemical Group, and industry sources. Components may not sum to totals because of rounding.

[a] Includes industrial tank and pipe.

Rigid urethane foams are manufactured primarily by four production processes, which must be distinguished because their CFC use and emissions characteristics differ.[12] Rigid slabstock is produced in large buns similar to flexible urethane buns and is cut to the desired size and shape for insulation and other applications. Laminated boardstock is produced in large sheets, often with aluminum, paper, or asphalt facing materials, and is used as a sheathing material in the construction market. Field spray foams are typically applied on the job site by small contractors as an insulation covering on industrial tanks and pipes and other structures. Pour in place (PIP) foams involve pouring a liquid mixture into a cavity, such as in the walls of an appliance cabinet. In some products, the pour in place technology employs a frothing process, which uses small amounts of CFC-12 in addition to CFC-11.

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[12] Detailed discussions of these production processes are contained in Arthur D. Little (1975), and Midwest Research Institute (1976b), Chapter IV. These descriptions are not reproduced here.

Table 3.C.2 shows rigid urethane foam output by product and production process for selected years. Projections for most of the markets in Table 3.C.2 are based directly on data obtained from and reviewed by industry sources. Much of the impressive growth of rigid urethane foam markets expected by 1982 is attributable to the residential construction and refrigeration markets. Residential construction is the newest and fastest growing market for rigid urethane insulation. The market penetration of laminated boardstock foam insulation in the residential sheathing market is currently about 20 percent, according to construction industry sources. Foam output projections for this insulation market are based on a fairly steady new housing market, with 1.7 million starts in 1982 and 1.9 million starts in 1990. However, the market penetration by rigid urethane insulation is expected to grow to about 42 percent in 1982 and 67 percent in 1990. Consequently, foam consumption in this market is expected to increase dramatically through 1982 and then grow at a slower pace from 1983 to 1990.

Estimates for rigid urethane insulation in refrigerators and freezers are based on IR&T projections of domestic unit shipments and on estimates of average foam content and future market penetration by foam insulation. According to producers of home appliances, in 1977 the average foamed refrigerator cabinet contained about 11.3 pounds of rigid urethane and the average freezer contained about 17.2 pounds. The market penetration in 1977 of foam insulation is reported by one raw material supplier to be 45 to 50 percent for refrigerators and as high as 90 percent for freezers. Because of increased concern for energy efficiency, average foam content and the market penetration of foam insulation are expected to rise in the future. The estimates in this report assume that by 1983 both markets will be completely penetrated and the average foam content will be 13 pounds for refrigerators and 19 pounds for freezers. As a consequence, foam output for the refrigeration market is expected to double between 1977 and 1982. After these markets are penetrated, growth in foam use will result only from increases in units shipped, reaching 181.4 million pounds in 1990.

Table 3.C.3 presents output projections for the nonurethane foams. The expected growth rate for total extruded sheet output is approximately 8.2 percent until 1982[13] and about half that rate from 1983 to 1990. Estimates for extruded PS insulation board are provided for the residential and commercial construction markets. According to industry sources, these markets account for virtually all extruded board output and in 1977 were of approximately equal size in terms of foam consumption. Extruded board foam output is expected to grow along with the

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[13] *Modern Plastics*, August 1978. Several industry sources, in comments on an interim report covering the nonurethane foams, indicated that these projections for 1977 to 1982 were optimistic. However, no substantive evidence or alternative projections were provided. Because of *Modern Plastics* close association with the industry and because of recent growth trends in extruded sheet markets, these projections were not adjusted downward prior to 1983.

## Table 3.C.2

## RIGID POLYURETHANE AND ISOCYANURATE FOAM OUTPUT BY PRODUCTION PROCESS, 1976 AND 1990

(Millions of pounds)

| Use | Slabstock | Laminated Boardstock | Field Spray | Pour in Place | Total |
|---|---|---|---|---|---|
| 1976 | | | | | |
| Construction | 16 | 60 | 72 | 14 | 162 |
| Commercial | 13 | 54 | 40 | 10 | 117 |
| Residential | 1 | 6 | -- | -- | 7 |
| Industrial | 2 | -- | 32 | 4 | 38 |
| Refrigeration | -- | -- | -- | 60 | 60 |
| Refrigerators | -- | -- | -- | 23 | 23 |
| Freezers | -- | -- | -- | 21 | 21 |
| Commercial | -- | -- | -- | 16 | 16 |
| Transportation | 4 | -- | 9 | 27 | 40 |
| Packaging | -- | -- | -- | 16 | 16 |
| Marine/flotation | -- | -- | 6 | 8 | 14 |
| Total CFC blown | 20 | 60 | 87 | 125 | 292 |
| 1990 | | | | | |
| Construction | 31 | 551 | 228 | 91 | 901 |
| Commercial | 23 | 323 | 127 | 80 | 553 |
| Residential | 4 | 228 | 6 | -- | 238 |
| Industrial | 4 | -- | 95 | 11 | 111 |
| Refrigeration | -- | -- | -- | 181 | 181 |
| Refrigerators | -- | -- | -- | 103 | 103 |
| Freezers | -- | -- | -- | 44 | 44 |
| Commercial | -- | -- | -- | 34 | 34 |
| Transportation | 1 | -- | 12 | 53 | 66 |
| Packaging | -- | -- | -- | 50 | 50 |
| Marine/flotation | -- | -- | 13 | 18 | 31 |
| Total CFC blown | 32 | 551 | 253 | 393 | 1,229 |

SOURCES: Based on Mobay Chemical Corporation (1978), Olin Chemical Group, and industry sources. See text for discussion. Components may not sum to totals because of rounding.

Table 3.C.3

NONURETHANE FOAM PRODUCTION, 1977 TO 1990
(Millions of pounds)

| Year | Extruded PS Sheet | Extruded PS Board | | | Extruded Polyolefin, Other | Total[a] Foam Output |
|---|---|---|---|---|---|---|
| | | Residential | Commercial | Total | | |
| 1977 | 321.9 | 26.6 | 26.5 | 53.1 | 30.0 | 405.0 |
| 1978 | 344.5 | 30.8 | 28.7 | 59.5 | 33.8 | 434.8 |
| 1979 | 368.9 | 35.7 | 31.0 | 66.7 | 38.0 | 473.6 |
| 1980 | 395.9 | 41.4 | 33.5 | 74.9 | 42.7 | 513.5 |
| 1981 | 425.1 | 48.1 | 36.1 | 84.2 | 48.1 | 557.4 |
| 1982 | 457.3 | 55.8 | 39.0 | 94.8 | 54.1 | 606.2 |
| 1983 | 476.0 | 61.0 | 40.8 | 101.8 | 58.2 | 636.0 |
| 1984 | 495.5 | 66.7 | 42.7 | 109.4 | 62.5 | 667.4 |
| 1985 | 515.7 | 72.9 | 44.6 | 117.5 | 67.2 | 700.4 |
| 1986 | 536.8 | 79.7 | 46.7 | 126.4 | 72.2 | 735.4 |
| 1987 | 558.7 | 87.1 | 48.8 | 135.9 | 77.7 | 772.3 |
| 1988 | 581.6 | 95.2 | 51.1 | 146.3 | 83.5 | 811.4 |
| 1989 | 605.4 | 104.0 | 53.4 | 157.4 | 89.8 | 852.6 |
| 1990 | 630.1 | 113.7 | 55.9 | 169.6 | 96.5 | 896.2 |

SOURCES: *Modern Plastics* (1978); Allied Chemical Corporation (1977); and industry sources.

[a] Total excludes expanded PS foam due to low market penetration of CFC blowing agents.

demand for insulation, with the residential market outpacing growth in the commercial market.[14]

## CFC Use

For most closed cell plastic foams, direct evidence on CFC use is not available, and it is necessary to compute CFC consumption from foam production data. On the basis of evidence regarding CFC usage rates, Tables 3.C.4 and 3.C.5 present baseline estimates of CFC use in rigid urethane and nonurethane foams, respectively.[15] For the rigid urethanes, CFC use is expected to nearly quadruple from 43.6 million pounds in 1977 to 158.5 million pounds in 1990.[16]

For the nonurethane foams, CFC use is 27.2 million pounds in 1977 and will more than double by 1990. Estimates of the largest nonurethane CFC consumer, extruded PS sheet, assume a market penetration of 64 percent for CFC-12 blown foam in extruded PS sheet markets and a CFC usage rate of 7.8 pounds per 100 pounds of CFC blown foam output. For the other nonurethane foams, the data are direct estimates of CFC use based on information from reliable industry sources. Estimates of CFC use in expanded PS foams are based on Arthur D. Little and Midwest Research Institute estimates for 1973 and 1974 and assume a growth rate of about eight percent annually.[17]

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[14] Some industry observers expect even higher rates of growth, and extruded board output in 1990 could be as high as 200 million pounds. In any event, the fact that Dow is developing products for new insulation applications and will soon add two plants that will increase Styrofoam capacity by 50 percent provides convincing evidence of high expected growth rates.

[15] Appendix F presents a more complete discussion of the methodology used to estimate CFC use and emissions rates in closed cell foams.

[16] These estimates include approximately 1.8 million pounds of CFC-12 in 1977, or 4.0 percent of total rigid urethane CFC use, and 4.3 million pounds of CFC-12 in 1990, or 2.7 percent of total use.

In summary, CFC use in closed cell plastic foams is currently significant and growing at a rapid rate. In 1977 total consumption of CFC in these products was about 71 million pounds. By 1990 annual CFC use in closed cell plastic foams is expected to treble to around 225 million pounds.

### Table 3.C.4

### Estimated CFC Use in Rigid Polyurethane and Isocyanurate Foam, 1960 to 1990

(Millions of pounds)

| | Insulation | | | | | | |
|---|---|---|---|---|---|---|---|
| Year | Construction | Refrigeration | Transportation | Total | Packaging | Marine/ Flotation | Total CFC Blown[a] |
| | | | Historical | | | | |
| 1960 | 0.1 | 0.6 | 0.6 | 1.3 | -- | 0.1 | 1.4 |
| ... | | | | | | | |
| 1965 | 2.5 | 2.6 | 2.1 | 7.2 | 0.1 | 0.6 | 7.9 |
| ... | | | | | | | |
| 1970 | 9.7 | 6.6 | 4.2 | 20.5 | 0.9 | 2.1 | 23.5 |
| 1971 | 10.7 | 7.3 | 4.1 | 22.1 | 0.7 | 1.5 | 24.3 |
| 1972 | 13.6 | 7.8 | 5.2 | 26.6 | 0.8 | 1.9 | 29.3 |
| 1973 | 17.0 | 9.0 | 7.1 | 33.2 | 1.1 | 2.1 | 36.4 |
| 1974 | 18.1 | 9.4 | 6.9 | 34.4 | 1.5 | 1.9 | 37.8 |
| 1975 | 20.7 | 9.0 | 6.8 | 36.5 | 1.6 | 1.8 | 39.9 |
| 1976 | 20.2 | 7.4 | 5.6 | 33.2 | 1.9 | 1.9 | 37.0 |
| 1977 | 24.8 | 8.8 | 5.9 | 39.5 | 2.2 | 1.9 | 43.6 |
| | | | Projected | | | | |
| 1978 | 30.8 | 10.3 | 6.0 | 47.1 | 2.4 | 2.0 | 51.5 |
| 1979 | 38.7 | 12.1 | 6.3 | 57.1 | 2.8 | 2.2 | 62.1 |
| 1980 | 45.9 | 14.2 | 6.6 | 66.7 | 3.1 | 2.3 | 72.1 |
| 1981 | 54.0 | 17.0 | 6.8 | 77.8 | 3.4 | 2.4 | 83.6 |
| 1982 | 62.8 | 20.3 | 7.1 | 90.2 | 3.6 | 2.6 | 96.4 |
| 1983 | 67.1 | 21.0 | 7.3 | 95.4 | 3.9 | 2.7 | 102.0 |
| 1984 | 72.1 | 21.5 | 7.6 | 101.2 | 4.1 | 3.0 | 108.3 |
| 1985 | 77.5 | 22.3 | 7.9 | 107.7 | 4.4 | 3.1 | 115.2 |
| 1986 | 83.2 | 22.9 | 8.1 | 114.2 | 4.6 | 3.3 | 122.1 |
| 1987 | 89.5 | 23.8 | 8.4 | 121.7 | 5.0 | 3.5 | 130.2 |
| 1988 | 96.2 | 24.9 | 8.7 | 129.8 | 5.3 | 3.6 | 138.7 |
| 1989 | 103.3 | 26.1 | 9.0 | 138.4 | 5.7 | 3.9 | 148.0 |
| 1990 | 111.0 | 26.4 | 10.8 | 148.2 | 6.1 | 4.2 | 158.5 |

SOURCES: Midwest Research Institute (1976b); Tables 3.D.1, 3.D.2, and 3.D.3; and industry sources. See text for assumptions on usage rates.

[a] Predominantly CFC-11. Includes less than five percent CFC-12 from frothed foam.

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[17] Even if this assumed growth rate were seriously in error, total CFC use in closed cell foams would not be significantly affected. As a point of reference, CFC use in expanded PS foams would have to increase at an average annual rate of 20 percent from 1977 to 1990 to reach even the modest use level of 10 million pounds in the latter year. This rate of growth would exceed that anticipated for *any* of the plastic foams, including rigid urethane insulation in construction applications, which is expected to average an annual growth rate of about 13 percent over this period.

## Table 3.C.5

## ESTIMATED CFC USE IN NONURETHANE FOAMS, 1970 TO 1990

(Millions of pounds)

| Year | Extruded PS Sheet | Extruded PS Board | Expanded PS Board | Extruded Polyolefin, Other[a] | Total CFC Use[b] |
|---|---|---|---|---|---|
| Historical | | | | | |
| 1970 | 6.5 | 1.4 | 0.3 | 2.9 | 11.1 |
| 1971 | 7.8 | 1.8 | 0.3 | 3.1 | 13.0 |
| 1972 | 9.4 | 2.2 | 0.4 | 3.3 | 15.3 |
| 1973 | 11.5 | 2.6 | 0.5 | 3.5 | 18.1 |
| 1974 | 13.7 | 3.1 | 0.8 | 4.4 | 22.0 |
| 1975 | 13.0 | 3.6 | 0.9 | 4.0 | 21.5 |
| 1976 | 13.1 | 4.2 | 0.9 | 4.5 | 22.7 |
| 1977 | 16.1 | 5.0 | 1.0 | 5.1 | 27.2 |
| Projected | | | | | |
| 1978 | 17.3 | 5.6 | 1.1 | 5.7 | 29.7 |
| 1979 | 18.5 | 6.3 | 1.2 | 1.4 | 32.4 |
| 1980 | 19.9 | 7.1 | 1.2 | 7.2 | 35.4 |
| 1981 | 21.3 | 8.0 | 1.3 | 8.1 | 38.7 |
| 1982 | 22.9 | 9.0 | 1.4 | 9.1 | 42.4 |
| 1983 | 23.9 | 9.7 | 1.5 | 9.8 | 44.9 |
| 1984 | 24.9 | 10.4 | 1.6 | 10.5 | 47.4 |
| 1985 | 25.9 | 11.2 | 1.8 | 11.3 | 50.2 |
| 1986 | 26.9 | 12.0 | 1.9 | 12.2 | 53.0 |
| 1987 | 28.0 | 12.9 | 2.1 | 13.1 | 56.1 |
| 1988 | 29.2 | 13.9 | 2.2 | 14.1 | 59.4 |
| 1989 | 30.4 | 14.9 | 2.4 | 15.1 | 62.8 |
| 1990 | 31.6 | 16.1 | 2.6 | 16.3 | 66.6 |

SOURCES: Table 3.D.3; Arthur D. Little (1975); *Modern Plastics* (1978); DuPont (1978a); and industry sources. Components may not sum to totals because of rounding.

[a] Contains some CFC-11, CFC-113, CFC-114, and CFC-115, as well as 40 to 60 percent CFC-12.

[b] Includes approximately 90 percent CFC-12.

### CFC Emissions

The emissions processes of the closed cell foams are perhaps the most complicated—and most controversial—of any of the nonaerosol uses of CFCs.[18] Most closed cell foam products are "nonprompt" CFC emitters. That is, a substantial portion of the CFC used in their production is retained within the cellular structure of the foam long after manufacture. Indeed, because of the importance of CFC as an insulating medium, a primary goal of foam insulation manufacturers is to retain a maximum amount of CFC in their product for as long as possible.

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[18] For a more complete discussion of the CFC emissions process from closed cell foams, see Appendix F.

The CFC consumed in the production of closed cell foams is lost to the atmosphere during one of three stages in the product life cycle. *Manufacturing emissions* occur before the closed cell foam leaves the production facility. These losses occur during the handling and storage of CFC and include emission during the actual foaming process. The CFC not emitted during manufacture enters the "bank" and is subject to possible future emission. *Normal use emissions* occur when CFC is diffused from the foam cells during the normal use of the product. (Under some circumstances, normal use emissions may continue even after the product has been removed from service.) *Disposal emissions* occur when foam-bearing products are scrapped. If a foam-bearing product is destroyed in such a manner as to rupture a significant portion of the foam cells, the CFC remaining at disposal will be emitted.

A small fraction of the CFC used is emitted during closed cell urethane foam manufacturing processes. For rigid urethane and isocyanurate foam this averages about 11 percent, and for PS board it averages about 10 percent. Actual manufacturing emissions rates vary among the rigid urethanes, depending upon the production process involved.

In contrast, manufacturing emissions for nonurethane foams are a higher share of use. Available evidence indicates that the production of extruded PS sheet releases 45 to 79 percent of CFC use, depending upon the nature of the manufacturing facility. The polyolefins appear to emit even a higher fraction of CFC use. Manufacturing losses amount to virtually all the CFC used in polypropylene production. Although industry sources present some conflicting evidence, the manufacturing facility also appears to be the fundamental emissions unit for polyethylene foam.

In further contrast to the case of the rigid urethanes and extruded board insulation, virtually all the CFC not emitted during production from extruded PS sheet and polyolefin foam is released to the atmosphere during the first year of foam life. Consequently, annual emissions from these "prompt," closed cell foams approximately equal annual CFC use.

The estimates of normal use emissions presented below are based on the theoretical literature on the "aging" process of CFC blown foam and on recent evidence from industry sources, which are currently investigating the k-factor degradation (or aging process) of CFC blown foam.[19] Several important features of the normal use emissions estimates should be noted.

First, initial versions of the simulation model developed to estimate closed cell foam emissions assumed a relatively short basic "half-life"[20] of 11.7 years for two-inch-thick rigid urethane foam with all faces exposed to the atmosphere. However, most industry sources strongly argue that this half-life, which is directly based on Norton's theoretical model,[21] results in serious overestimates of normal use emissions. In this report, a substantially higher basic half-life of 60 years for two-inch-thick exposed foam is employed. This figure is based on the preliminary results of ongoing industry research, which has tested a large number of foam samples and found minimum half-lives of about 40 years, with a reasonable central measure of the likely half-life of 50 to 60 years.

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[19] The thermal conductivity, or k-factor, of these products depends upon the CFC content of the foam cells as a fraction of all gases contained in the cells. Over time, the thermal properties of CFC blown foam generally degrade due to the infusion of air into or diffusion of CFC from the foam cells.

[20] The half-life is a useful summary statistic of the normal use emissions function. It is defined as the age at which 50 percent of the CFC originally banked in a closed cell foam product has been released to the atmosphere.

Second, it is extremely important to realize that no single normal use emissions function can be meaningfully applied to all closed cell foams. The thickness of a foam product has dramatic effects on normal use emissions rates, with thinner foams releasing CFC at a much faster pace.[22] Recent evidence indicates that foam thicknesses vary systematically across products and our emissions estimates account for these differences.

An equally important consideration is whether a foam product employs facing materials resistant to CFC diffusion—i.e., whether the foam is "clad." In this report, all laminated boardstock and pour in place foams (except in packaging) are assumed to be clad. Slabstock and field spray foams are assumed unclad. The half-life of clad foams is estimated to be four times the half-life of similar unclad foams. That is, clad foams take approximately four times as long on average to emit a given amount of CFC as do unclad foams of equal thickness.[23]

Normal use emissions from extruded PS board insulation are also characterized by a relatively long half-life. For these insulation products, a half-life of nearly 50 years is used for unclad foam and nearly 200 years for clad foam, based on polystyrene aging data provided by industry sources.

In practice, the extent of normal use emissions from a foam product depends upon the particular physical characteristics of the product and its environment. For example, rigid urethane foam facing materials include aluminum foil, polyethylene coated paper, asphalt impregnated felt paper, laminated plastics, perlite, and others. When properly bonded to the foam, aluminum foil facings may virtually eliminate normal use emissions, regardless of foam thickness. The other facing materials are less effective (and may be completely ineffective) CFC barriers. Unfortunately, neither data availability nor existing knowledge of emissions processes are adequate to account fully for these differences in product characteristics. As a result, our estimates of normal use emissions are representative only of aggregate releases from an entire foam market (e.g., residential construction). In general, the emissions pattern of a particular piece of foam will differ from the average pattern presented here.

The disposal of closed cell foam products also represents a potentially important source of CFC emissions, although many of these emissions will not occur until long after 1990. Average lifetimes for products containing nonprompt closed cell foams vary substantially, from one year for packaging applications to 80 years for residential structures.

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[21] Norton (1967).

[22] This conclusion applies only if at least one face of the foam product is effectively exposed to the atmosphere. See the discussion of cladding below.

[23] Mathematically, the effect of quadrupling the half-life is equivalent to assuming foams are clad only on one side, with one face effectively exposed to the atmosphere. This procedure has several justifications. First, this assumption is realistic for many types of closed cell foam. For example, many foamed refrigerator cabinets are made with plastic inner liners, which are not an effective CFC barrier, although the steel outer wall is. Second, it is difficult to classify many product categories as clad or unclad. Some of the rigid foam classified as clad may not have effective CFC barriers on either face of the foam, while others may have effective barriers on both faces. Thus, the above cladding assumptions do not appear unreasonable as an average approximation.

The average lifetime of a product has a significant effect on emissions patterns. For example, disposal emissions are relatively less important for longer-lived products simply because the CFC has more time to diffuse to the atmosphere during normal product use. In some cases, when a foam-bearing product is destroyed, all or part of the residual CFC in the foam cells may remain there indefinitely or continue to escape at the normal use emissions rate. Alternatively, all remaining CFC at the time of disposal may be emitted immediately. Due to inadequate information about disposal practices, the emissions estimates presented below adopt the latter assumption, which can be interpreted as a "worst case" scenario.[24]

Estimates of CFC emissions from the rigid urethane and isocyanurate foams are presented in Table 3.C.6. Total annual emissions from the rigid urethanes are estimated at 13.3 million pounds in 1976 and are expected to more than quadruple by 1990. Throughout the 1970 to 1990 period, the largest emission source among the rigid urethanes is insulating foams in construction applications. In 1977, the construction market accounts for 38 percent of total rigid urethane emissions and by 1990, because of the rapid growth of this foam market, construction accounts for a majority (53 percent) of emissions. Insulation applications in general account for 81 percent of rigid urethane emissions in 1977 and 85 percent in 1990.

Emissions from the nonurethane foams are summarized in Table 3.C.7. Although the nonurethane foams consume significantly less CFC, nonurethane emissions are comparable in magnitude to rigid urethane emissions, because the nonurethanes are dominated by relatively "prompt" emitters. In 1976 total nonurethane emissions are estimated at 19.2 million pounds and by 1990 annual emissions should more than double. The nonprompt emitting extruded PS board insulation accounts for a relatively small fraction of total nonurethane foam emissions through 1990 (three percent in 1977 and six percent in 1990).

Perhaps more important than total emissions levels is the fact that emissions patterns vary dramatically across closed cell foam applications of CFCs. With the exception of extruded PS board, the nonurethane foams emit virtually all of their CFCs during the first year of foam life. However, while emissions from some of the polyolefins, such as polypropylene foam, occur almost entirely at the manufacturing facility, normal use emissions account for about 21 to 55 percent of extruded PS sheet losses, depending upon the nature of the production process.

Table 3.C.8 illustrates the distribution of emissions by stage of product life for the major rigid urethane foam applications. The most important determinants of the relative importance of manufacturing, normal use, and disposal emissions are

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[24] Very recent preliminary experimental evidence suggests the potential of chemical reactions, which may occur during the aging process of rigid urethane and isocyanurate foams. Such reactions have potentially profound implications for the significance of the rigid urethanes as a source of CFC emissions. Briefly stated, some industry sources argue that CFC-11 may react over long periods of time with the rigid urethane polymer of the foam cells, exchanging a chlorine atom for a hydrogen atom. If such reactions do occur, some of the CFC-11 banked within rigid urethane products would be transformed to CFC-21, which is believed a less serious threat to the ozone layer, prior to release to the atmosphere. It must be emphasized that this research is in the extremely early stages, and neither Rand nor other sources can verify its accuracy. Although the possibility of such a terrestrial CFC-11 sink is not taken into account in this analysis, it warrants mention here because of the implication that rigid urethane emissions during normal product use and disposal may represent a much less severe ozone hazard than the estimates presented below suggest.

## Table 3.C.6

### ESTIMATED CFC EMISSIONS FROM RIGID POLYURETHANE AND ISOCYANURATE FOAMS, 1960 TO 1990

(Millions of pounds)

| Year | Insulation | | | | Packaging | Marine/ Flotation | Total Emissions[a] |
|---|---|---|---|---|---|---|---|
| | Construction | Refrigeration | Transportation | Total | | | |
| Historical | | | | | | | |
| 1960 | 0.0 | 0.1 | 0.1 | 0.2 | 0.0 | 0.0 | 0.3 |
| ... | | | | | | | |
| 1965 | 0.4 | 0.4 | 0.4 | 1.3 | 0.1 | 0.1 | 1.5 |
| ... | | | | | | | |
| 1970 | 2.0 | 1.2 | 1.4 | 4.6 | 0.9 | 0.5 | 6.0 |
| 1971 | 2.3 | 1.4 | 1.7 | 5.4 | 0.8 | 0.4 | 6.6 |
| 1972 | 2.9 | 1.7 | 2.1 | 6.7 | 0.8 | 0.6 | 8.1 |
| 1973 | 3.6 | 2.0 | 2.8 | 8.4 | 1.0 | 0.6 | 10.0 |
| 1974 | 4.1 | 2.2 | 3.1 | 9.4 | 1.3 | 0.7 | 11.4 |
| 1975 | 4.7 | 2.3 | 3.5 | 10.5 | 1.5 | 0.7 | 12.7 |
| 1976 | 4.9 | 2.2 | 3.6 | 10.7 | 1.8 | 0.8 | 13.3 |
| 1977 | 5.9 | 2.6 | 4.0 | 12.5 | 2.1 | 0.9 | 15.5 |
| Projected | | | | | | | |
| 1978 | 7.0 | 3.1 | 4.4 | 14.5 | 2.3 | 1.0 | 17.8 |
| 1979 | 8.8 | 3.7 | 4.8 | 17.3 | 2.6 | 1.2 | 21.1 |
| 1980 | 10.4 | 4.4 | 5.2 | 20.0 | 3.0 | 1.3 | 24.3 |
| 1981 | 12.4 | 5.2 | 5.5 | 23.1 | 3.3 | 1.4 | 27.8 |
| 1982 | 14.7 | 6.1 | 5.8 | 26.6 | 3.5 | 1.6 | 31.7 |
| 1983 | 16.3 | 6.8 | 6.1 | 29.2 | 3.8 | 1.7 | 34.7 |
| 1984 | 18.1 | 7.5 | 6.3 | 31.9 | 4.0 | 1.8 | 37.7 |
| 1985 | 20.0 | 8.2 | 6.4 | 34.6 | 4.3 | 1.9 | 40.8 |
| 1986 | 21.9 | 8.8 | 6.6 | 37.3 | 4.5 | 2.0 | 43.8 |
| 1987 | 24.1 | 9.5 | 6.7 | 40.3 | 4.8 | 2.1 | 47.2 |
| 1988 | 26.3 | 10.1 | 6.9 | 43.3 | 5.2 | 2.2 | 50.7 |
| 1989 | 28.8 | 10.8 | 7.1 | 46.7 | 5.5 | 2.4 | 54.6 |
| 1990 | 31.3 | 11.3 | 7.5 | 50.1 | 5.9 | 2.5 | 58.6 |

SOURCES: Based on Tables 3.C.1, 3.C.2, and 3.C.4. See text for assumptions. Components may not sum to totals because of rounding.

[a] Emissions are predominantly CFC-11. Includes less than five percent CFC-12.

the average lifetime of the foam-containing product and the characteristics of the foam itself (primarily the presence of cladding material and foam thickness). In construction applications, for example, disposal emissions are a small fraction of total emissions, because the long expected lifetimes of these structures implies that very little construction insulation will be scrapped prior to 1990. Normal use emissions are relatively high in the construction market because of the relatively thin foam used in the residential and commercial markets[25] and the predominance of unclad foams in industrial construction. In contrast, transportation applications of

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[25] Laminated boardstock comprises the majority of the residential and commercial construction rigid urethane markets. For this type of foam an average thickness of 0.75 inches is assumed for residential markets and 1.25 inches for commercial markets. In contrast, the assumed average thickness of transportation applications of rigid urethane foam is 3.0 inches.

### Table 3.C.7

### ESTIMATED CFC EMISSIONS FROM NONURETHANE FOAMS, 1970 TO 1990

(Millions of pounds)

| Year | Extruded PS Sheet | Extruded PS Board | Expanded PS Board | Extruded Polyolefin,[a] Other | Total Emissions[b] |
|---|---|---|---|---|---|
| Historical | | | | | |
| 1970 | 6.5 | 0.2 | 0.3 | 2.9 | 9.9 |
| 1971 | 7.8 | 0.3 | 0.3 | 3.1 | 11.5 |
| 1972 | 9.4 | 0.3 | 0.4 | 3.3 | 13.4 |
| 1973 | 11.5 | 0.4 | 0.5 | 3.5 | 15.9 |
| 1974 | 13.7 | 0.5 | 0.8 | 4.4 | 19.4 |
| 1975 | 13.0 | 0.6 | 0.9 | 4.0 | 18.5 |
| 1976 | 13.1 | 0.7 | 0.9 | 4.5 | 19.2 |
| 1977 | 16.1 | 0.8 | 1.0 | 5.1 | 23.0 |
| Projected | | | | | |
| 1978 | 17.3 | 0.9 | 1.1 | 5.7 | 25.0 |
| 1979 | 18.5 | 1.1 | 1.2 | 1.4 | 27.2 |
| 1980 | 19.9 | 1.2 | 1.2 | 7.2 | 29.5 |
| 1981 | 21.3 | 1.4 | 1.3 | 8.1 | 32.1 |
| 1982 | 22.9 | 1.6 | 1.4 | 9.1 | 35.0 |
| 1983 | 23.9 | 1.8 | 1.5 | 9.8 | 37.0 |
| 1984 | 24.9 | 1.9 | 1.6 | 10.5 | 38.9 |
| 1985 | 25.9 | 2.1 | 1.8 | 11.3 | 41.1 |
| 1986 | 26.9 | 2.3 | 1.9 | 12.2 | 43.3 |
| 1987 | 28.0 | 2.6 | 2.1 | 13.1 | 45.8 |
| 1988 | 29.2 | 2.8 | 2.2 | 14.1 | 48.3 |
| 1989 | 30.4 | 3.1 | 2.4 | 15.1 | 51.0 |
| 1990 | 31.6 | 3.4 | 2.6 | 16.3 | 53.9 |

SOURCES: Based on Tables 3.C.3 and 3.C.5. See text for assumptions. Components may not sum to totals because of rounding.

[a] Includes 40 to 60 percent CFC-12. Remainder consists of CFC-11, CFC-113, CFC-114, and CFC-115.

[b] Includes approximately 85 percent CFC-12.

rigid urethane are characterized by relatively short-lived assets (10 years on average) and predominantly thicker, clad foam. Consequently, normal use emissions are much less significant in transportation applications and product disposal is the most important source of potential CFC emissions, accounting for more than 70 percent of annual 1990 emissions.[26]

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[26] The sensitivity of the emissions estimates in Tables 3.C.6 to 3.C.8 to alternative assumptions regarding CFC usage and emission rates is extensively analyzed in interim reports submitted for industry review. The sensitivity analysis indicates estimated emission levels are relatively insensitive to alternative foam output growth rates, CFC usage rates, and manufacturing emission rates, within reasonable ranges for these variables. In contrast, changes in the assumptions underlying estimates of postmanufacturing emissions—including the basic half-life, foam thickness and effects of cladding for normal use emissions, and the percentage of remaining CFC emitted at disposal—have a significant effect on the magnitude and distribution of CFC emissions from closed cell foams. Because the conclusions of the sensitivity analysis are essentially unchanged, they are not reproduced in full detail here.

### Table 3.C.8

### DISTRIBUTION OF ANNUAL CFC EMISSIONS FROM RIGID POLYURETHANE AND ISOCYANURATE FOAM BY STAGE OF PRODUCT LIFE, 1976 AND 1990

(Percent)

| Product | Manufacture | Normal Use | Disposal |
|---|---|---|---|
| 1976 | | | |
| Construction | | | |
| Commercial | 44.5 | 55.5 | <0.1 |
| Residential | 47.5 | 52.5 | 0.0 |
| Industrial | 37.1 | 62.2 | 0.7 |
| Refrigeration | | | |
| Refrigerators | 40.7 | 33.0 | 26.3 |
| Freezers | 44.6 | 38.3 | 17.1 |
| Commercial | 73.8 | 25.1 | 1.1 |
| Transportation | 21.5 | 10.4 | 68.1 |
| Packaging | 12.0 | 6.3 | 81.7 |
| Marine/flotation | 30.8 | 28.4 | 40.8 |
| Total rigid urethanes | 33.8 | 31.6 | 34.6 |
| 1990 | | | |
| Construction | | | |
| Commercial | 40.2 | 55.7 | 4.0 |
| Residential | 29.5 | 70.0 | 0.5 |
| Industrial | 28.6 | 58.3 | 13.1 |
| Refrigeration | | | |
| Refrigerators | 29.4 | 20.9 | 49.7 |
| Freezers | 20.7 | 17.9 | 61.4 |
| Commercial | 38.4 | 21.8 | 39.8 |
| Transportation | 21.1 | 7.1 | 71.9 |
| Packaging | 11.4 | 6.2 | 82.5 |
| Marine/flotation | 22.6 | 19.1 | 58.3 |
| Total rigid urethanes | 29.2 | 38.7 | 32.4 |

SOURCES: Based on Tables 3.C.1, 3.C.2, and 3.C.4. Manufacturing emission rates vary by production process. Assumes half-life of 60 years for two inch unclad foam and adjusts normal use estimates for foam thickness. Disposal emissions assume that 100 percent of remaining CFC is released when final products are scrapped. Components may not sum to 100.0 percent because of rounding.

## The Closed Cell Foam CFC "Bank"

Our analysis of rigid urethane and isocyanurate foams and extruded PS board insulation suggests that by 1990 these closed cell foams will consume a cumulative total of nearly 2 billion pounds of CFC. Yet, emissions from these products will amount to less than one-third of cumulative use over the same period of time. The remaining CFC is, of course, contained in the closed cell foam CFC bank, awaiting potential future release to the atmosphere.

Table 3.C.9 illustrates the CFC bank for closed cell foams in 1976 and 1990. These data summarize the fate of CFC used in closed cell foam formulations from the inception of these markets through 1990. By 1976, cumulative CFC use in nonprompt emitting closed cell foams was about 340 million pounds. Of this total, we estimate that about 90 million pounds was released to the atmosphere and 250 million pounds remained inventoried within foam products being used in the United States. By 1990, cumulative CFC use is expected to be around 1.9 billion pounds. Cumulative releases are expected to be about 623 million pounds, divided approximately evenly between product manufacture, normal use, and disposal. Thus, by 1990, the closed cell foam CFC bank is expected to contain nearly 1.3 billion pounds of CFC, including approximately 14 percent CFC-12 and 86 percent CFC-11.

Table 3.C.9

CUMULATIVE CFC EMISSIONS AND THE CLOSED CELL FOAM CFC BANK, 1976 AND 1990

(Millions of pounds)

| Product | Cumulative Use | Cumulative Emissions | | | CFC Bank |
|---|---|---|---|---|---|
| | | Manufacture | Normal Use | Disposal | |
| 1976 | | | | | |
| Total rigid urethane[a] | 317.0 | 38.3 | 26.2 | 22.8 | 229.8 |
| Construction | 139.0 | 14.4 | 15.5 | <0.1 | 109.2 |
| Refrigeration | 82.6 | 11.1 | 5.1 | 1.0 | 65.3 |
| Transportation | 62.9 | 8.7 | 3.1 | 11.7 | 39.4 |
| Packaging | 11.5 | 1.3 | 0.7 | 8.8 | 0.8 |
| Marine/flotation | 21.0 | 2.8 | 1.8 | 1.3 | 15.1 |
| Total extruded PS board[b] | 22.9 | 2.3 | 1.1 | <0.1 | 19.5 |
| Total | 339.9 | 40.6 | 27.3 | 22.8 | 249.3 |
| 1990 | | | | | |
| Total rigid urethane[a] | 1,748.9 | 195.8 | 205.7 | 191.7 | 1,155.8 |
| Construction | 1,095.9 | 110.0 | 159.3 | 6.4 | 819.9 |
| Refrigeration | 353.8 | 45.7 | 26.4 | 43.0 | 238.8 |
| Transportation | 169.6 | 24.2 | 9.3 | 73.3 | 62.9 |
| Packaging | 68.0 | 7.6 | 4.1 | 53.9 | 2.6 |
| Marine/flotation | 61.1 | 8.3 | 6.6 | 15.1 | 31.6 |
| Total extruded PS board[b] | 165.0 | 16.5 | 13.5 | 0.3 | 134.8 |
| Total | 1,913.9 | 212.3 | 219.2 | 192.0 | 1,290.6 |

SOURCES: Based on Tables 3.C.6 and 3.C.7. Data show cumulative totals from 1960 to year indicated.

[a] Predominantly CFC-11. Includes less than five percent CFC-12.

[b] Includes CFC-12 only.

The CFC bank is obviously an important phenomenon for the closed cell foams. In 1990, releases from the closed cell foam bank alone (i.e., normal use and disposal emissions) will be nearly 44 million pounds annually. Even if CFC use in closed cell foams were banned in 1990, the CFC bank could release this amount of CFC each year—a level which exceeds total emissions in 1978 from all closed cell foams—until the year 2020.[27]

## INDUSTRY AND MARKET CHARACTERISTICS

### Firms

There are hundreds of firms directly involved in the manufacture of closed cell foams, ranging in size from extremely small and specialized contractors who apply field spray foams to high volume producers of laminated boardstock, extruded polystyrene and other closed cell foams. For some closed cell foams, the manufacturers' activities are related solely to foam production. For other foam products, rigid urethane foam accounts for only one step in the production process of the final product.

There are relatively few rigid urethane slabstock producers. The two major producers are the CPR Division of Upjohn and Owens-Corning Fiberglass. Other producers include Dacar Chemical Products and Elliot Company, Inc. Manufacturers of laminated boardstock are more numerous. At least 17 have been identified, located in all regions of the country except the less-populated Northern Great Plains and Pacific Northwest states.

Foam insulation in the refrigeration markets is typically applied by the manufacturer of the final product. By the mid 1980s virtually all of these producers are expected to manufacture foamed cabinets. Major producers who use rigid urethane foam in transportation applications include Fruehauf Corporation, Timpte, Inc., Trailmobile, Great Dane Trailers, Inc., and Hackney Brothers Body Company.

In addition, at least 31 firms provide rigid urethane systems to customers who then actually apply the rigid urethane foam. These "systems houses," which are typically small and usually involved with field spray or pour in place foam, are also located throughout the country, with concentrations in the Midwest, Northeast, Texas, and California. A large number of small contractors apply field spray foams on the job site. The Urethane Foam Contractors Association, a trade association representing these firms, has about 300 member organizations, most of which appear to have 10 or fewer employees and spray less than 500,000 pounds of foam annually. According to Midwest Research Institute (1976, p. IV-35), in 1976 more than 650 firms owned foam spray equipment and purchased rigid urethane systems for on-site application.

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[27] Under the assumptions of the simulation model, emissions following a cessation of the use of CFC blowing agents would differ somewhat from this. If, for example, CFC use were prohibited after 1990, annual emissions from the projected CFC bank would initially be near the 44 million pound 1990 level. Annual emissions levels might actually increase for a time after 1990 as longer-lived products are disposed, then gradually decrease. However, emissions from the closed cell foams would not be eliminated probably for more than a century.

A substantial number of firms are involved in the production and fabrication of nonurethane foams. One recent publication lists 105 producers of polystyrene sheet, film, and block. However, these firms include a large number of expanded PS producers and polystyrene foam fabricators, which are not likely to consume a significant quantity of CFC blowing agents.

The use of CFC by polystyrene sheet and board producers appears fairly concentrated, relative to the rigid urethane foam industry. A substantial fraction of the CFC used in these products is accounted for by no more than ten firms and in some products the degree of concentration in foam output and CFC use is even higher. In the large stock tray and egg carton markets, which account for over 50 percent of extruded sheet output, three producers are dominant: Mobil Chemical Company, Dolco Packaging Corporation, and Huntsman Container Corporation, which together produced over 90 percent of all foamed egg cartons in 1977. Mobil is also the largest producer of foamed stock trays and, along with W. R. Grace Foampac Division and Western Foam Pak, accounts for nearly 90 percent of this polystyrene foam market. The output of extruded sheet single service food containers is only slightly less concentrated, with six firms manufacturing about 84 percent of these products. Several nonurethane foam products are produced by a single firm. Until recently, Dow Chemical U.S.A. has been the sole producer of virgin extruded PS board and Owens-Illinois is the only known domestic producer of nonthermoformed PS foam sheet containers.

The primary material inputs for rigid urethane foams are polyol and polyphenyl-polymethylene-isocyanate. According to industry sources, the primary suppliers of isocyanate to rigid urethane producers are Upjohn, Mobay, and Rubicon. Production capacities for isocyanate production have recently been increased by Mobay and Rubicon. In addition, BASF Wyandotte and ARCO will become isocyanate suppliers by 1982, and Mobay plans further capacity increases by 1981. Major suppliers of polyether polyols to the urethane foam industries include Union Carbide, Dow, BASF Wyandotte, Olin, E. R. Carpenter, Mobay, and Jefferson Chemical. The first four firms accounted for about 70 percent of polyol capacity in 1977. The major building block of polystyrene foam, aside from the blowing agent, is polystyrene bead. In 1977, the five major polystyrene bead suppliers were ARCO Polymers, Inc., BASF Wyandotte, Crown Molding Company, Dow Chemical, and Foster Grant.

Like the other characteristics of closed cell foam markets, the economic characteristics of closed cell foam producers vary. To assess these characteristics it is useful to categorize foam producers into two groups defined above: those who primarily produce a finished foam product and those who produce a final product that merely contains CFC blown foam.[28]

The former group of firms includes the producers of laminated boardstock and rigid urethane slabstock and many of the small rigid urethane foam spray contractors and systems houses, as well as virtually all of the producers of nonurethane foams. With the exceptions noted below, these foam markets appear relatively easy to enter and exit and are competitive in nature.[29]

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[28] Obviously, firms in the former category can be (and often are) part of a larger corporate organization engaged in a variety of other economic activities.

[29] According to industry sources, while there is no evidence of a lack of competition, the extruded PS board insulation market is not relatively easy to enter or exit, primarily because of the large capital

Available evidence strongly suggests that economies of scale are not a significant phenomenon in the production of foam products (as opposed to final products containing closed cell foams).[30] One observation reinforcing this conclusion is that the larger nonurethane foam producers tend to be multiplant firms. Second, firms that anticipate substantial growth (as many do) almost invariably plan to meet the increase in demand by constructing additional plants rather than by expanding old plants. Third, the plants producing a particular foam product do not appear to vary dramatically in size, as measured by plant capacity.

This evidence indicates the existence of a fairly well defined optimal plant size for these foam markets, when both production and transportation costs are considered. Consequently, it is likely that any significant output reductions in response to regulation would be accomplished primarily by plant closures, rather than by smaller reductions in all (or most) facilities.

Fixed costs (including depreciation and supervisory and maintenance labor) in the production of closed cell foam products are a relatively small fraction of total costs.[31] This generalization applies to the production of virtually all of the plastic foams. These industries are highly materials sensitive, and with few (if any) exceptions, materials costs represent the largest single cost item for a foam producer. On the basis of available evidence, the variable (or direct) costs of closed cell foam production, including material inputs and direct labor, account for at least two-thirds of total costs. For some firms, this figure may be as high as 90 percent, with a reasonable central measure in the range of 75 to 80 percent.

While materials costs dominate, the costs of CFC itself are not a particularly large component of total costs. For rigid urethane foam products, CFC costs appear to account for only four to 10 percent of total production costs, depending upon the type of foam produced. For polystyrene sheet, blowing agent costs account for about eight percent of total costs and perhaps 15 to 20 percent of materials costs. The cost of blowing agents is a larger fraction of total costs for the polyolefins, which normally consume more CFC per pound of foam output.

Economic characteristics differ from the above for firms that produce final products containing CFC blown closed cell foams. These firms include producers of refrigeration devices and transportation vehicles using foam insulation and manu-

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investment required and the fact that historically the production process has been proprietary. However, *Modern Plastics* (1978) reports the recent introduction of processing equipment that should allow entry into even this market. In fact, within the last year Gerd Lester Corporation and UC Industries have entered the extruded PS board market, the latter with a patented extrusion technology.

[30] This discussion is largely based on evidence from confidential questionnaires distributed to foam producers, with the cooperation of the Society of the Plastics Industry. The evidence refers to 13 firms producing closed cell foam in a total of 25 plants. It should be noted that the firm-specific discussion in the text is not based on any rigorous statistical analysis of these data. To preserve the confidentiality of firm-specific data, the text discussion is largely qualitative in nature and any numerical data presented are based on evidence from at least three firms.

[31] Industry sources argue that at least two exceptions exist. First, at least one major producer of polypropylene foam employs recovery and recycle equipment (discussed below), which they assert adds significantly to fixed costs. While cost data on this particular production process are not available, it should be noted that for virtually all the producers of all other closed cell foams, fixed costs could double and still not account for a majority of total costs. Second, according to industry sources, some of the lower volume nonurethane foams require highly skilled technicians for their production and these skills are in relatively short supply. This situation does suggest the existence of a factor in relatively fixed supply and indicates that the short-run responsiveness of these industries to regulation may differ significantly from the long-run response.

facturers of items with foam cores, such as boat hulls. In general, entry and exit appear less prevalent in these industries. Larger capital investments are required to enter these industries and the lead time between the initial planning stages of a new production line and full scale operation can be substantial.[32] In addition, fixed costs are typically a higher fraction, and CFC costs a lower fraction, of total production costs than in those industries that produce solely a foam product.

### Employment

Direct estimates of the number of employees involved in the production of CFC blown foam are not available. However, from information received from a number of closed cell foam producers, we estimate that in 1977, 9,400 workers were directly involved with the production of CFC blown closed cell foam. Of this total, approximately 4,200 workers were directly involved in rigid urethane foam production and 5,200 in CFC blown nonurethanes. Given expected growth rates, employment levels will rise rapidly along with CFC blown foam output. In the absence of regulation, employment should rise to about 17,000 workers in 1982 and 27,500 in 1990, with the rigid urethanes accounting for the majority of workers during these later years.

These employment estimates apply to direct, maintenance, and supervisory workers involved in foam production. They do not include employment in expanded PS production, nonurethane foam fabrication, polystyrene bead production, or the production of other inputs purchased by foam producers. Unfortunately, available evidence is insufficient for even a rough calculation of the number of workers employed in these endeavors. Nevertheless, the indirect labor effects of regulatory action intended to reduce significantly the output of closed cell foams are potentially greater than the direct labor effects. According to one industry source, the number of workers indirectly related to the output of some nonurethane foams may be three to four times the number of directly related workers.[33]

## OPTIONS TO REDUCE EMISSIONS

For most closed cell foams, options to reduce CFC emissions are quite limited. Alternative blowing agents that do not seriously compromise the quality of the foam product are not available at the present time. Moreover, there are no nonfoam insulation materials with thermal conductivity properties comparable to CFC blown foam insulation. Consequently, except for some packaging applications, short of eliminating the services provided by closed cell foams, options for reducing emissions would be directed at one of the three stages of emissions—product manufacture, normal use, and disposal. Unfortunately, with the possible exception of some nonurethane foams, few options aimed directly at the emissions processes of closed cell foams appear promising at this time, as the following discussion illustrates.

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[32] An example of the level of investment is provided by a relatively small plant that has recently gone on-line producing single door refrigerators. According to industry sources, because this refrigerator market has a small and declining share of total sales, this plant would be shut down if required to use non-CFC blown insulation, and capital losses alone would total $80 to $90 million. Required lead times for major changes in the production process for home refrigeration appliances are a minimum of two years and can be as much as five years or more before full scale operation is achieved.

[33] Statement of Jon Laing, Dow Chemical U.S.A., in EPA (1977a), p. 226.

## Foam Insulation

Because of the importance of CFCs to insulation performance, strong market incentives currently exist to retain as much CFC in these products as possible, at least until disposal. Thus, manufacturers attempt to maximize the amount of CFC originally banked in foam insulation, or, equivalently, to reduce manufacturing losses. Moreover, there are also incentives to clad products or otherwise reduce normal use emissions, subject to cost constraints, in order to preserve product quality over time.

Without exception, both industry and publicly available sources report that there are no existing substitutes for CFCs that would preserve the relative thermal efficiency of foam insulation. Because of their inertness[34] and low thermal conductivity, the CFC-11 in rigid urethane and CFC-12 in extruded PS board are ideal blowing agents for foam insulation. Although rigid urethane insulation can be produced without CFC by using carbon dioxide as a blowing agent, the resulting product would have a k-factor roughly twice as high as existing products.

The most promising avenue for the development of alternative inputs appears to lie with several experimental varieties of CFCs. According to DuPont, three possible substitutes for CFC-11 in rigid urethane foam are CFC-123, CFC-133a, and CFC-141b, although they are in the early (and uncertain) stages of their development.[35] These chemicals have k-factors comparable to CFC-11 (about 10 percent higher) and are believed less harmful to stratospheric ozone. However, these alternatives to CFC-11 pose several problems. Although the toxicological properties of these chemicals are not fully known, existing evidence indicates that CFC-133a is embryotoxic and CFC-141b is reportedly a weak mutagen. Moreover, none of these chemicals is commercially available in the United States. A production process is under development for CFC-141b, but, aside from its alleged mutagenicity, this blowing agent is flammable, a serious concern for insulation producers.

Recovery of manufacturing emissions appears infeasible for a large fraction of the closed cell foam insulation markets. Hundreds of firms produce field spray and pour in place foams in construction and other applications. These firms operate nonstationary manufacturing facilities, moving from job site to job site. Consequently, carbon adsorption or other known techniques for CFC recovery do not appear technically feasible in these applications.

CFC recovery does appear technically feasible for laminated boardstock, slabstock, and some PIP rigid urethane foam and possibly for extruded PS board, insofar as these represent in-plant (or stationary) sources of manufacturing emissions. However, the economics in these cases strongly suggest that recovery has virtually no chance of voluntary implementation and little better chance of being an enforceable mandated control option. These plants typically produce much less foam by weight than a flexible urethane plant and they use less CFC. On the basis of available information from laminated boardstock producers and of the manufacturing emissions rates presented earlier, the amount of CFC available for recovery in these plants can be (liberally) estimated as less than 100,000 pounds annually per plant. If collection efficiencies and recovery costs comparable to those for flexible urethane are achieved, only about 50,000 pounds of CFC would be recovered annually,[36] and the value of this small amount of CFC appears insufficient to cover even the operating costs of the unit. Consequently, firms that produce insulating foams may have strong incentives not to comply with recovery requirements, even if forced to purchase the equipment. Because a relatively large and growing number of plants are involved,[37] the enforcement costs of such a strategy would very likely be prohibitive.

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[34] As noted above, the inertness of CFC-11 in rigid urethane has very recently been questioned, because of the possibility of chemical reactions within the foam during the aging process.

[35] DuPont (1978a), p. IV-20.

In limited circumstances, cladding foams with CFC diffusion resistant facings is a potential method of altering the CFC emissions pattern of foam insulation. Since incentives currently exist to prevent normal use emissions, the use of cladding materials is increasingly prevalent.[38] In many of the foam insulation applications that do not now use cladding, such as field spray applications, it would be difficult to apply CFC barriers. Even in applications where cladding improvements might be made, it is unlikely that long-run emission levels would be significantly affected, because cladding is a *delay* strategy. Unless steps are also taken to curb disposal emissions, cladding will probably reduce normal use CFC emissions in the short run only at the expense of higher disposal emissions in the future.[39]

Ultimately, effective options for limiting long-run emissions from closed cell foams must consider emissions during product disposal. While disposal emissions account for only 31 percent of pre-1990 total emissions from nonprompt closed cell foams, post-1990 disposal emissions will become more significant as increasing numbers of foam-bearing products are disposed.

Several methods for collecting or destroying CFC from used foam insulation are available. Industry sources have noted that CFC-11 can be destroyed by incineration at a temperature in excess of 1,200 degrees centigrade, although the emission of the halogen hydrides, HCl and HF, resulting from this process would require the installation of flue-gas scrubbers in the incinerator.[40] Alternatively, several processes are available for chemically dissolving disposed or scrap foam to recover and reuse the polymer.[41] According to industry sources, collection of the CFC remaining in these foam cells would pose no fundamental technical problems.

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[36] This figure is likely to decline in the future for laminated boardstock, because manufacturers are actively seeking ways to reduce material waste, which is the primary cause of CFC losses during production. One large producer of laminated boardstock anticipates reducing waste losses to three to four percent, which would reduce CFC manufacturing losses by about two-thirds.

[37] The exact number of laminated boardstock, slabstock, and PIP plants is not known. However, at least 21 firms produce laminated boardstock or slabstock, and it is not uncommon for a firm to have four or more plants. In addition, because of economic considerations discussed above, the number of plants involved can be expected to increase proportionately with rapidly growing industry output levels.

[38] The rigid urethane market share of foams that are clad, according to our admittedly rough classification, is expected to rise from 63 percent in 1976 to 77 percent in 1990. (See Table 3.C.2.)

[39] This conclusion depends upon disposal practices and the fate of the remaining CFC when a product is scrapped. If disposal results in the indefinite retention of the remaining CFC, cladding could reduce long run emissions levels.

[40] This information was conveyed to Rand by Mobay Chemical Co. in a Bayer Technical note (1978).

[41] See, for example, Ulrich et al. (1978).

While the prevention of disposal emissions is feasible once used foam is available, the actual collection of foam insulation from discarded products, whether caused by regulatory mandate or economic incentives, poses immense problems. During any given year, the number of potential disposal emissions sources is extremely large. For example, by 1990, there will be nearly four million residential structures with foam insulation, a similar (if not larger) number of commercial structures, thousands of industrial tanks and pipes, well over 100 million foam-insulated home refrigeration appliances, tens of thousands of foam-bearing transportation vehicles, boat hulls, and commercial refrigeration devices, and so on. All of these millions of potential disposal emissions sources have uncertain destruction dates. A relatively small (but absolutely large) number of units will, in fact, be destroyed during any given year, but exactly which units will be destroyed and in what manner cannot be predicted.

Moreover, the amount of CFC available for recovery is quite small per product. For example, a typical foam-insulated refrigerator surviving an average 17 years contains less than 1.5 pounds of CFC-11 at the time of disposal. Even a truck trailer, which uses relatively large amounts of CFC in its thick insulated walls, will contain only about 40 pounds of CFC after 10 years of life, on the basis of the emissions assumptions discussed above.

In both of these examples, and in virtually all other foam insulation applications, the final product must be dismantled to allow access to the foam. While cost estimates for collecting disposed foam are not available, the labor inputs alone would appear to be substantial relative to the CFC that could be collected. Consequently, strong incentives would likely exist to avoid recovery at disposal, and the enforcement costs of requiring such action would almost certainly be prohibitive.

## Noninsulating Foams

For extruded PS sheet, extruded polyolefin, and the other prompt-emitting closed cell foams, which emit virtually all of their original CFC during the first year of foam life, two options for emissions reduction can be considered. These include the use of alternative blowing agents and CFC recovery and recycle during manufacture.

The primary candidate for using a substitute blowing agent is extruded PS sheet, which currently consumes a large quantity of pentane blowing agents. Available evidence suggests that pentane could be used as the blowing agent for virtually all thermoformed sheet products, which account for about 81 percent of total PS sheet output in 1977 and 74 percent of CFC use.[42]

Several considerations are relevant for assessing regulations that require or induce substitution of pentane blowing agents for CFC. First, despite the fact that pentane costs less per pound than CFC-12, production costs are higher for pentane blown PS sheet, because higher densities result and, therefore, more material inputs are required. Second, conversion to pentane would impose very high capital costs. Third, pentane blowing agents can pose a serious fire hazard to production workers, especially if the polystyrene resin becomes ignited, and several plants using pentane have reportedly been totally destroyed by fire.[43] Finally, pentane has very recently been the subject of several local regulatory actions. These blowing agents are low-boiling gasoline fractions suspected of contributing to smog. According to industry sources, at least two states, Georgia and California, are actively seeking ways to prevent pentane emissions by regulation, and other states are expected to follow.

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[42] Some industry sources argue that pentane is not well suited, although technically acceptable, for the production of "deep draw" items, which are growing relative to other PS sheet markets.

Recovery of manufacturing emissions is an alternative to pentane substitution for extruded PS sheet. Largely in response to potential regulations, producers of both pentane blown and CFC blown PS sheet are currently investigating the possibilities for recovery and recycle of blowing agents. While these inquiries are still in the early stages and have not yet produced any usable data for assessing recovery and recycle of CFC, this option cannot be ruled out at this time. It should be noted that, to our knowledge, no operational recovery and recycle equipment has been developed for PS sheet products, and information on the costs and effectiveness of recovery is necessarily speculative at this time. In contrast, the major producer of extruded polypropylene foam does practice recovery at the present time. This recovery process employs carbon adsorption technology, achieves an overall recovery efficiency of 80 percent, and is economical at current CFC prices.[44] While recovery from extruded PS sheet is undoubtedly less attractive from an economic viewpoint, the large quantities of CFC-12 available for collection in a single plant and the probable absence of chemical contaminants in the air stream suggest that recovery is possible as a voluntary industry response to regulatory stimuli and might be an enforceable control candidate.

## CFC DEMAND SCHEDULES

The price responsiveness of CFC use in the closed cell foams differs between insulation and packaging foams. For foam insulation, there are no currently available substitutes for CFC blowing agents. Consequently, the only way to reduce CFC use in these products is to reduce the use of foam insulation itself. While an examination of product bans is beyond the scope of this study, an analysis of the energy implications of not using foam insulation illustrates that the demand for CFC in these applications should be insensitive to the price of CFC and that this very large use of CFC could not be substantially reduced without a very large energy penalty.

In contrast, CFC use in extruded PS sheet can be significantly affected by higher CFC-12 prices. The previous discussion identifies two options for reducing CFC use—CFC recovery and pentane conversion—that can be implemented without necessarily reducing the amount of foam produced. For these products, a demand analysis similar to that for flexible urethane foam is presented, predicated on the assumption of an inelastic demand for final foam products within the range of CFC prices considered.

Substitute products are available in some PS sheet markets, such as egg cartons and some other food service items where paper and foam products coexist. In these cases, it is more likely that higher foam prices caused by regulation will result in lower foam sales. Although the final product price effects of the mandatory control candidates are not expected to be dramatic, the effects of the inelastic demand assumption are to overestimate the pecuniary costs of regulation, which are ultimately reflected in higher expenditures by consumers for packaging materials, and to underestimate other costs that will occur as markets shift from foam to nonfoam products, such as the temporary dislocation of workers and potential plant closures.

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[43] See the discussion above at p. 90.

[44] DuPont (1978b).

Available information is inadequate for a detailed demand analysis of CFC use in the remaining closed cell foams, including extruded polyolefin foam, expanded PS, and the noninsulation applications of rigid urethane. For these foam products, which currently account for less than 13 percent of closed cell foam CFC use, the following sections of this report adopt the conservative assumption of a completely inelastic CFC demand schedule.

## Foam Insulation

The energy savings attributable to foam insulation in construction, refrigeration, and transportation applications depend upon a wide variety of variables. These include the construction details of the application, location, climate, the efficiency of the heating or cooling system, fuel costs, life styles, and a myriad of other variables. Consequently, precise calculation of the implications of not using foam insulation is exceedingly difficult. However, industry sources unanimously agree that energy savings from CFC insulation are substantial, a view supported by our analysis.

The approach adopted here is to calculate the energy consumption of a "typical" application in each foam market when foam insulation and, alternatively, a likely substitute material are employed. Energy usage estimates are based on design thermal resistance (or R) values for alternative materials, assumptions regarding the construction detail of the insulation application, and on assumed annual heating and/or cooling requirements.[45] The aggregate energy implications of substituting other materials for foam insulation are based on the energy penalty computed for selected applications and projections of the future stock of foam insulation in the economy.

Table 3.C.10 summarizes the analysis of energy implications in the selected applications. The data show the annual increase in energy requirements (in millions of Btu) for each one million pounds of foam insulation replaced by a substitute material. The consequences of substitution vary. In a residential structure, foam insulation typically complements fiberglass batt insulation, which accounts for most of the thermal resistance of the wall, ceiling, or floor assembly. Consequently, the relative increase in energy consumption when fiberboard sheathing is used in this application is relatively low. For the remaining applications, foam insulation is the primary source of thermal resistance, and relative energy penalties are much higher, ranging from a 54.1 percent increase in energy usage per million pounds of foam insulation replaced in commercial construction to 99 percent for refrigerated truck trailers.

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[45] R-values are from the ASHRAE *Handbook of Fundamentals* and from industry sources.

## Table 3.C.10

## ANNUAL ENERGY USAGE WITH FOAM AND NONFOAM INSULATION IN SELECTED APPLICATIONS

| Foam Insulation Application | Substitute Material | Energy Usage[a] | | |
|---|---|---|---|---|
| | | Foam (millions of Btu) | Substitute (millions of Btu) | Percent Increase |
| Residential structure[b] | Fiberboard | 8.9 | 10.2 | 14.9 |
| Commercial structure[b] | Perlite | 6.8 | 9.9 | 54.1 |
| Industrial tank | Fiberglass | 17.1 | 31.2 | 82.7 |
| Refrigerator[c] | Fiberglass or $CO_2$ foam | 39.9 | 71.4 | 79.1 |
| Freezer/commercial refrigeration[c] | Fiberglass or $CO_2$ foam | 17.9 | 34.1 | 90.7 |
| Refrigerated truck trailer | Fiberglass | 3.3 | 6.6 | 99.0 |

SOURCE: See text for method of calculation. Based on design values for energy usage. Actual energy usage varies with field conditions.

[a] Data show energy usage per million pounds of foam insulation and for alternative materials of equal thickness and surface area.

[b] Based on rigid urethane insulation.

[c] Calculations are illustrative only, because technical considerations require nonfoam insulation materials to be thicker than current foam insulation thicknesses.

Energy usage for the substitute materials in Table 3.C.10 assumes that each application is well insulated but does not use foam insulation.[46] The analysis does not account for the likelihood that greater thicknesses of alternative materials would be employed in the absence of foam insulation, because the thicknesses that would actually result cannot be predicted with available information. In particular, the calculations for home refrigerators in Table 3.C.10 are illustrative only, because it is not technically feasible[47] to maintain desired temperatures in the unit unless greater thicknesses of fiberglass or carbon dioxide blown foam are employed. Consequently, Table 3.C.10 somewhat overestimates actual energy penalties. At the same time, the analysis makes no estimate of other penalties from forgoing the use of foam insulation, such as possibly significant sacrifices in interior volume (especially for refrigerators) and, according to producers of the final products, substantial increases in final product prices.[48]

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[46] As an illustration, the "typical" residential structure in this analysis is a single family frame house, with sheathing insulation (foam or fiberboard) and fiberglass in all exterior walls, ceilings, and floors. Heating requirements of 6,000 degree days per winter season are assumed. For the fiberglass insulation nominal R-values of 13 and 19 are used for walls and ceiling, respectively. The structure is also assumed to contain energy efficient glass windows and doors. If the calculations were based on a less energy efficient structure comparable to those produced when energy prices were lower, the relative energy penalty of substituting away from foam insulation would be greater.

[47] That is, when using the standard size compressor and evaporator currently in these units.

[48] A further qualification is that the estimates of Table 3.C.10 include only the direct energy requirements resulting from greater heat loss through exterior walls. In some cases, secondary energy penalties

Table 3.C.11 assesses the aggregate energy costs of substituting away from foam insulation, based on a hypothetical ban on these products beginning in 1980. The first column of Table 3.C.11 shows the increase in energy consumption during 1990 that would result if foam insulation were replaced by alternative materials in all products produced during or after 1980. On the basis of the energy costs per million pounds of foam insulation replaced and estimates of post 1980 production contained in the 1990 baseline stock, energy consumption would be increased in 1990 by the equivalent of 6.4 billion gallons (or 152 million barrels) of fuel oil. Refrigeration applications account for nearly half of this substantial energy penalty, with estimated energy losses in the construction markets only slightly smaller. The annual energy penalties for years after 1990 would be even larger because the projected stock of foam products in the economy is growing at a rapid rate.

Table 3.C.11 also presents estimates of annual energy costs per pound of CFC use avoided. Even for residential construction, where the energy saving from CFC blown foam is low relative to other applications, energy penalties are substantial per pound of CFC use avoided. The typical residential structure assumed in this analysis consumes about 550 pounds of rigid urethane foam, containing 67 pounds of CFC-11, which will not be completely emitted for a period of 80 years on average. The replacement of foam insulation by fiberboard increases the energy consumption of the structure by the equivalent of about 73 gallons of fuel oil annually, or by nearly 1,500 gallons during the first 20 years of the structure's useful life. Since foam insulation adds only about $150 to $300 to construction costs, and CFC blowing agents account for less than 10 percent of foam costs, the cost of CFC relative to the energy savings from using foam insulation is trivial. As a result, there is virtually no chance that substitution to nonfoam insulations could be induced by higher CFC prices, within the price range considered.

## Extruded PS Sheet

Like the flexible urethane foams, the price responsiveness of CFC use in thermoformed extruded PS sheet depends upon the costs of alternative blowing agents and CFC recovery, and varies with plant size. On the basis of information contained in confidential questionnaires distributed with the cooperation of the Society of the Plastics Industries, the demand analysis for extruded PS sheet distinguishes three classes of plants: large plants, medium plants, and small plants, consuming 750,000, 500,000, and 350,000 pounds of CFC-12 per year, respectively.

Pentane conversion in extruded PS sheet products significantly increases production costs. The capital costs of pentane conversion in this analysis are estimated at $460,000 for structural modifications required by the fire hazards of pentane, plus $80,000 per extruder line. With small, medium, and large plants containing two, three, and four extruders, respectively, the capital costs of pentane conversion

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will also occur. For example, if foam insulation were not used in refrigerated truck trailers, heavier body construction would be required as well as a larger compressor in the refrigeration unit itself, resulting in higher gasoline consumption of the vehicle.

## Table 3.C.11

### ANNUAL ENERGY PENALTIES OF SUBSTITUTING NONFOAM FOR FOAM INSULATION BEGINNING IN 1980

| Foam Market | Penalty in 1990[a] (billions of equivalent gallons of fuel oil) | Penalty per Pound of CFC Use Avoided[b] (equivalent gallons of fuel oil) |
|---|---|---|
| Construction | | |
| Residential[c] | 0.3 | 1.1 |
| Commercial[c] | 1.5 | 2.6 |
| Industrial | 1.3 | 11.7 |
| Refrigeration[d] | | |
| Refrigerators | 2.3 | 18.0 |
| Freezers/commercial | 0.9 | 9.2 |
| Transportation | 0.2 | 2.8 |
| Total | 6.4 | -- |

SOURCE: Based on Tables 3.C.1, 3.C.2, and 3.C.10. Components do not sum to totals because of rounding.

[a] Assumes operating efficiency of 70 percent. (1 gallon fuel oil = 98,000 Btu.)

[b] Based on rigid urethane. For extruded PS board, energy penalty is about 30 percent less on average, but varies by application.

[c] 1990 energy penalty includes losses from rigid urethane and extruded PS board markets.

[d] Assumes the operating efficiency of fuel oil at the powerhouse is 33 percent and that electrical energy cools with a coefficient of performance of 2.83. (1 gallon fuel oil = 130,746 Btu.)

are $620,000 for small plants, $700,000 for medium plants, and $780,000 for large plants.[49] For decisions regarding pentane conversion, an investment criterion requiring capital payback in 4.2 years is assumed. Other costs associated with pentane conversion include $90,000 annually for additional labor, higher energy consumption estimated at $0.12 per pound of CFC replaced, and insurance costs estimated at two percent of the costs of capital.[50]

The most significant cost of pentane conversion appears to involve higher usage of material inputs in the production process. Some industry sources argue that as much as 20 percent more material is required to produce a given level of final output with pentane than with CFC blowing agents. While this figure may apply to some plants, it is unlikely that pentane-related material costs are generally this severe, and this analysis assumes a 10 percent increase in required material inputs for conversion to pentane.[51]

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[49] See Sweetheart Plastics (1978). Other industry sources argue that the capital costs of pentane conversion are significantly lower: about $250,000 for structural modifications, plus $80,000 for each extruder line.

[50] See DuPont (1978a).

[51] Assuming prices of $0.46 per pound for CFC, $0.18 for pentane, and $0.44 for polystyrene resin, if pentane actually increased materials usage by 20 percent, PS sheet producers who use pentane should

The second possible response of PS sheet producers to higher CFC prices (other than simply reducing output or paying higher CFC-12 prices) is CFC recovery. The cost parameters of CFC recovery in PS sheet plants are assumed identical to those for flexible urethane foam plants. That is, recovery costs include $960,000 per plant for capital, $26,800 annually for maintenance, labor, and insurance, and $0.014 per pound of recovered CFC for the energy costs of the recovery unit.

Although the lack of adequate specific information on CFC recovery from PS sheet necessarily makes an analysis of this response speculative, these cost parameters nevertheless appear very conservative. In contrast with recovery costs in a flexible foam plant, which may be significantly increased by the presence of isocyanates and other chemical contaminants in the air stream to be treated, extruded PS sheet foam formulations are more than 99 percent polystyrene resin and blowing agent. While some industry sources argue that the recovery process may be complicated by the presence of PS resin particles, there are no indications that recovery costs would be affected as significantly as for flexible urethane foam.[52]

In addition, manufacturing emissions from PS sheet may be concentrated at points within the plant to a greater extent than for flexible urethane foam. As a consequence, it is likely that producers of PS sheet can achieve higher collection efficiencies for a given level of capital costs. This analysis accounts for this possibility by assuming that 50 percent of CFC use is recovered for reuse.[53]

The response of polystyrene producers to higher CFC-12 prices will depend upon where the regulated price of CFC-12 stabilizes (i.e., the long-run price). For sufficiently small price increases, the most likely response is simply to pay higher CFC prices. On the basis of the conservative cost parameters described above, for large PS sheet plants CFC recovery is the most profitable course of action at long-run CFC-12 prices between $0.70 and $1.82 per pound, with pentane conversion minimizing production costs above this price range. For medium sized plants, production costs are minimized by CFC recovery if the price of CFC-12 is expected to range from $1.04 to $1.78 and by pentane conversion at higher prices. For small plants, no action is taken to reduce emissions unless a regulated CFC price of $1.48 results, where recovery is economical. At CFC prices above $1.69, small firms would minimize production costs by converting to pentane.

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be willing to invest immediately as much as $920,000 to convert to CFC-12. We are aware of no substantial capital costs required for this conversion. Moreover, CFC reduces plant fire hazards as well as materials costs. While pentane's market share of thermoformed sheet production continues to decline gradually, available evidence indicates that this blowing agent is still used to manufacture significant amounts of virtually every type of thermoformed PS sheet product. This evidence suggests that the 20 percent materials penalty cannot be generally applicable. Consequently, the 10 percent figure is assumed.

[52] In particular, the capital cost used here is based on an assumed gas flow of 20,000 CFM, this being required in flexible slabstock plants because of the very low (0.02) TLV of TDI. Since TDI is not present in PS, it is likely that substantially lower gas flows are possible. Capital costs are directly proportional to the gas flow, and thus would likely be much lower than estimated here. This case may be extremely conservative, as a result.

[53] Actual measurements taken in a number of foam plants for an unpublished industry study show that manufacturing emission rates for PS sheet range from 45 percent of CFC use to 79 percent, with an average facility emitting 63 percent. The CFC releases occur primarily at three points in the production process—extrusion, thermoforming, and scrap regrind—which together account for about 95 percent of manufacturing emissions. For an average facility, recovery and reuse of 50 percent of total CFC use implies an 80 percent collection efficiency.

Table 3.C.12 summarizes the above demand analysis for extruded PS sheet. The demand schedule indicates that a price increase of $0.24 per pound (or 52 percent) is required to induce a nine percent reduction in emissions.[54] To achieve a reduction of 36 percent (or 50 percent of CFC use in thermoformed products) a price increase of over $1 per pound is required, indicating that emissions reduction from PS sheet is subject to significantly increasing costs. At a long-run CFC-12 price of $1.82, the analysis indicates that the use of CFC in thermoformed sheet products will be minimal, and only emissions from nonthermoformed foams remain. At this price, we estimate the use of pentane blowing agents would be 14.5 million pounds greater in 1980 and 22.6 million pounds greater in 1990 than in the baseline case. Nonthermoformed products use only CFC-12 blowing agent and available information does not allow a rigorous demand analysis. For these products, the following sections of this report assume a completely inelastic demand for CFC.[55]

Table 3.C.12

CFC-12 DEMAND SCHEDULE FOR EXTRUDED POLYSTYRENE SHEET, 1980 AND 1990
(Millions of pounds)

| CFC-12 Price (1976 $ per pound) | Induced Activity | 1980 | | 1990 | |
|---|---|---|---|---|---|
| | | CFC Reduction[a] | Total CFC Use[b] | CFC Reduction[a] | Total CFC Use[b] |
| 0.46 | None | -- | 19.9 | -- | 31.6 |
| 0.70 | Large plants recover | 1.8 | 18.1 | 2.8 | 28.8 |
| 1.04 | Medium plants recover | 3.6 | 14.5 | 5.7 | 23.1 |
| 1.48 | Small plants recover | 1.8 | 12.7 | 2.8 | 20.3 |
| 1.69 | Small plants convert | 1.8 | 10.8 | 2.8 | 17.5 |
| 1.78 | Medium plants convert | 3.6 | 7.2 | 5.7 | 11.8 |
| 1.82 | Large plants convert | 1.8 | 5.4 | 2.8 | 9.0 |

SOURCE: See text for method of calculation. Assumes 25 percent of CFC use in large plants, 50 percent in medium plants, and 25 percent in small plants.

[a] Shows incremental reduction in CFC emissions from indicated activity.

[b] Shows total CFC-12 use at indicated price level.

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[54] The closed cell foam questionnaires reveal that PS sheet plants do not significantly vary in size. Most plants for which data are available are comparable to the medium plant assumed in this analysis, although some small and large plants exist. Consequently, Table 3.C.12 assumes that 50 percent of CFC use in thermoformed sheet products occurs in medium plants and 25 percent each in small and large plants. This assumption does not affect the estimated prices at which emissions reduction activities occur. Nor does it affect the conclusions that at a price of $1.48, CFC use in thermoformed products is 50 percent less than in the baseline projections and at $1.82, only CFC use in nonthermoformed products remains.

[55] Although pentane conversion does not appear a likely voluntary response to higher CFC prices for producers of nonthermoformed PS sheet, CFC recovery may occur. However, because no information is available on emissions within nonthermoformed PS sheet plants, this potential response is not included in the demand schedule.

These results are sensitive to several important assumptions. In particular, according to some industry sources, the capital costs of pentane conversion may be as much as $200,000 less per plant than the data assumed by Table 3.C.12, and the estimated $90,000 increase in annual labor costs also may be a significant overestimate. With lower estimates of pentane conversion costs, small plants would convert to pentane at a CFC-12 price of $1.18 and would never practice CFC recovery. While medium and large plants would still find that recovery minimizes costs in some price range, they would convert to pentane at lower CFC-12 prices than indicated above, and CFC use in thermoformed products would be minimal at a price of $1.44 per pound, rather than at $1.82 as in Table 3.C.12. Because the objective of the analysis in Sec. IV is to estimate an upper bound on the level of taxes or marketable permit prices required to achieve desired emissions reductions, the less elastic demand curve in Table 3.C.12 is used for that analysis.

Another important qualification is that the above analysis ignores possible regulations on the use of pentane, because of its contribution to smog creation. If firms are required to recover pentane as a result of such regulations, the demand schedule of Table 3.C.12 would not be affected at prices below $1.69, because the economics of CFC recovery are unaffected. However, pentane conversion in PS sheet would not be a likely outcome of higher CFC prices. Assuming the recovery costs noted above, the minimum CFC-12 price at which voluntary conversion would occur is $2.33 per pound for large plants.

Finally, Table 3.C.13 presents the demand schedule used in the analysis of Sec. IV for CFC-11 and CFC-12 in all closed cell foams. Based on the analysis of the energy savings from foam insulation, CFC use in rigid urethane insulation and extruded PS board, which account for nearly 90 percent of CFC-11 use and about 30 percent of CFC-12 use at current CFC prices, will not be significantly affected by higher CFC prices within the range considered. The reductions of CFC-12 use in Table 3.C.13 are based on the preceding demand analysis of extruded PS sheet. CFC use for the closed cell foams combined is not highly sensitive to higher CFC prices, with a substantial price increase to $1.82 per pound reducing total CFC use by only 13.5 percent in 1980 and 10 percent in 1990. Of the CFC use remaining at this higher price, foam insulation accounts for about 80 percent.

## MANDATORY CONTROL CANDIDATES

Among the closed cell foams, candidates for mandatory controls are analyzed only for CFC recovery and pentane conversion in thermoformed extruded PS sheet.[56] Either control candidate could be implemented as a retrofit or new source standard. Briefly summarized, a CFC recovery mandate would impose substantially lower costs per pound of emissions avoided than mandated conversion

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[56] CFC recovery may be a viable control candidate for nonthermoformed PS sheet products as well. However, because of the paucity of data available on emissions from these products, nonthermoformed foam is excluded from this analysis.

### Table 3.C.13

### CFC DEMAND SCHEDULE FOR CLOSED CELL FOAMS BY TYPE OF CFC, 1980 AND 1990

(Millions of pounds)

| CFC Price (Constant 1976 $) | 1980 | | 1990 | |
|---|---|---|---|---|
| | Total CFC-11 Use[a] | Total CFC-12 Use | Total CFC-11 Use[a] | Total CFC-12 Use |
| 0.46 | 73.2 | 34.3 | 162.4 | 62.7 |
| 0.70 | 73.2 | 32.5 | 162.4 | 59.9 |
| 1.04 | 73.2 | 28.9 | 162.4 | 54.2 |
| 1.48 | 73.2 | 27.1 | 162.4 | 51.4 |
| 1.69 | 73.2 | 25.2 | 162.4 | 48.6 |
| 1.78 | 73.2 | 21.6 | 162.4 | 42.9 |
| 1.82 | 73.2 | 19.8 | 162.4 | 40.1 |

SOURCES: Table 3.C.12. Assumes demand for CFCs in foam insulation, expanded PS foam, and polyolefin foam is completely inelastic. See text for discussion.

[a] Includes less than five percent CFC-113, CFC-114, and CFC-115.

to pentane, although the total emissions reduction of CFC recovery is only half as large. Because of the higher costs of pentane conversion and possible adverse effects on worker safety, the mandatory control benchmark emissions level for comparison with marketable permits includes mandatory CFC recovery for existing and new PS sheet plants, but excludes pentane conversion.

For thermoformed PS sheet producers, mandated CFC recovery applying to existing as well as new plants would increase the fixed costs of production by an estimated $256,000 per plant annually (including amortized capital expenses, insurance and other costs), based on the data of the previous section. CFC recovery also reduces material expenditures, resulting in net annual costs of about $89,000 for large plants, $144,000 for medium plants, and $177,000 for small plants. Consequently, the cost per pound of CFC emissions avoided varies from $0.24 to $1.02, depending upon plant size.

The aggregate costs of a CFC recovery mandate in thermoformed extruded PS sheet plants are reported in Table 3.C.14. The emissions reduction potential of the mandate is 7.2 million pounds in 1980 and 11.3 million pounds in 1990, with a cumulative reduction of about 103 million pounds. Assuming that the number of PS sheet plants increases proportionately with industry output,[57] the total costs of a CFC recovery mandate are estimated at $4.6 million in 1980 and $7.0 million in 1990, averaging about $0.61 per pound of emissions avoided. From 1980 to 1990, the present value of direct costs of regulation are $38.8 million (discounted at 11 percent annually).

Mandated pentane conversion would increase both the fixed and variable costs

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[57] This assumption biases total cost estimates upward, because average plant size should increase under CFC recovery mandate and the per pound cost of emissions avoidance is smaller for larger firms.

### Table 3.C.14

### EFFECTS OF MANDATED CFC RECOVERY IN EXTRUDED POLYSTYRENE SHEET PLANTS

| Plant Size[a] | Emissions Reduction (millions of pounds) | | | Total Costs (millions of $) | | | Cost per pound[d] ($) |
|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 1980-1990[b] | 1980 | 1990 | 1980-1990[c] | |
| Large | 1.8 | 2.8 | 25.8 | 0.4 | 0.7 | 3.8 | 0.24 |
| Medium | 3.6 | 5.7 | 51.5 | 2.1 | 3.3 | 18.4 | 0.58 |
| Small | 1.8 | 2.8 | 25.8 | 2.0 | 3.0 | 16.7 | 1.02 |
| Total | 7.2 | 11.3 | 103.0 | 4.6 | 7.0 | 38.8 | 0.61 |

SOURCE: See text for method of calculation. Assumes mandate applies to existing and new plants. Cost estimates are in constant (1976) dollars. Components may not sum to totals because of rounding.

[a] Assumes 25 percent of CFC use is in large plants, 50 percent in medium plants, and 25 percent in small plants.

[b] Cumulative emissions reduction from 1980 to 1990, inclusive.

[c] Present value of 1980 to 1990 net costs, discounted at 11 percent.

[d] Calculated from individual plant data.

of PS sheet production. Estimates of the per plant costs of pentane conversion in thermoformed PS sheet plants are presented in Table 3.C.15. For nonthermoformed PS sheet products, mandated pentane conversion could be equivalent to a product ban, unless the regulation included appropriate exemptions or allowed other emissions-reduction activities, such as CFC recovery.

### Table 3.C.15

### ESTIMATED ANNUAL COSTS PER PLANT OF MANDATED CONVERSION TO PENTANE BLOWING AGENTS IN EXTRUDED PS SHEET

(Dollars)

| Production Costs | Large Plants | Medium Plants | Small Plants |
|---|---|---|---|
| Increase in fixed expenditures[a] | 291,630 | 270,950 | 250,270 |
| Increase in material costs | 306,750 | 204,500 | 143,150 |
| Total | 598,380 | 475,450 | 393,420 |

SOURCE: See text for basis of calculations.

[a] Includes amortized capital expenses, insurance, and additional labor.

Table 3.C.16 summarizes the total emissions and cost effects of substituting pentane for CFC-12. The emissions-reduction potential of pentane conversion is twice as large as for CFC recovery. However, the direct costs of regulation are also substantially higher. The total annual costs of the mandate are estimated at $14.4 million in 1980 and $22.4 million in 1990, averaging about $0.96 per pound of emissions avoided. The present value of cumulative costs over the 1980 to 1990 period is $123.0 million.

Table 3.C.16

EFFECTS OF MANDATED CONVERSION TO PENTANE BLOWING AGENTS IN EXTRUDED POLYSTYRENE SHEET PLANTS

| Plant Size[a] | Emissions Reduction (Millions of pounds) | | | Total Costs (millions of $) | | | Cost per pound[d] ($) |
|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 1980-1990[b] | 1980 | 1990 | 1980-1990[c] | |
| Large | 3.6 | 5.7 | 51.5 | 3.0 | 4.8 | 25.5 | 0.80 |
| Medium | 7.3 | 11.3 | 103.0 | 7.1 | 10.9 | 60.7 | 0.95 |
| Small | 3.6 | 5.7 | 51.5 | 4.3 | 6.7 | 36.8 | 1.12 |
| Total | 14.5 | 22.6 | 206.0 | 14.4 | 22.4 | 123.0 | 0.96 |

SOURCE: See text for method of calculation. Assumes mandate applies to existing and new plants. Cost estimates are in constant (1976) dollars. Components may not sum to totals because of rounding.

[a] Assumes 25 percent of CFC use is in large plants, 50 percent in medium plants, and 25 percent in small plants.

[b] Cumulative emissions reduction from 1980 to 1990, inclusive.

[c] Present value of 1980 to 1990 annual costs, discounted at 11 percent.

[d] Calculated from individual plant data.

New source standards in the PS sheet industry would confront problems similar to those discussed for flexible foams. Because production costs are higher in new plants than in existing facilities, new source standards create strong incentives to increase production levels in existing plants and strong disincentives to construct new plants. The effect of this behavior would be to significantly delay any effects of new source standards on emissions. However, because of the historical tendency of this industry to expand almost exclusively through additional plants, we do not anticipate that new plant construction would be avoided beyond the mid-1980s. Consequently, extruded PS sheet may be one of the few product areas where new source standards would have a modest impact on pre-1990 CFC emissions.

Currently, there are at least 16 producers of CFC blown thermoformed PS sheet, producing foam in as many as 30 plants. By 1990, the baseline number of plants is expected to increase to about 45 to 50. If new source standards were implemented in 1980 and if existing plants could increase output by 25 percent without exceeding the considerably higher mandated production costs in new plants, it is unlikely that the standards would have any impact on emissions prior to 1984. By 1990, probably no more than 10 new plants, accounting for less than 20 percent of annual thermoformed production, would be subject to regulation. Consequently, the annual emissions effects of the new source standard even a decade after promulgation would be less than 20 percent of a retrofit standard, and the cumulative emissions reduction from 1984 to 1990 would be less than eight percent of the 1980 to 1990 reduction of a retrofit standard.

For the plants subject to regulation, the costs imposed by new source standards would be comparable to the costs per pound of emissions avoided for the retrofit controls. However, additional costs would be incurred even before the standards had any emissions impact, because plants existing prior to the date of the standard would be induced to increase production to inefficient levels.

Under the assumption that final product demand curves are inelastic, the costs of mandated controls will be borne by final consumers in the form of higher prices. Because the final product in the case of extruded PS sheet is foam itself, the relative increase in the prices of these packaging items will be somewhat larger than in other CFC applications. Assuming that product prices rise enough to return firms to competitive profit levels, price increases are estimated at about 3.8 percent on average for mandated CFC recovery or about 12 percent for mandated pentane conversion.

As is the case with flexible urethane foam, even if the demand for extruded PS sheet foam is completely inelastic, regulation will place smaller plants at a relative cost disadvantage and they may lose some foam markets to larger competitors. In addition, the existence of nonfoam substitutes for several PS sheet products suggests that regulated firms may lose some of their markets to nonfoam alternatives. While precise estimates of these impacts cannot be computed from available data, as many as 1,800 workers might be temporarily dislocated due to the regulations.

## CONCLUSIONS

Previous studies of nonaerosol CFC applications have concluded that the closed cell foams are a relatively unimportant source of CFC use and emissions. In contrast, this analysis indicates that closed cell foams currently consume a significant amount of CFCs and may become the largest nonaerosol CFC user by 1990 in the absence of regulation. Similarly, CFC emissions from closed cell foams are substantial, rising to over 100 million pounds in 1990. The closed cell foams are the largest contributor to the CFC bank, and by 1990 the stock of closed cell foams in the economy will contain nearly 1.3 billion pounds of CFC-11 and CFC-12 awaiting potential future release. Releases from the bank alone, during normal product use and product disposal, are expected to total nearly 44 million pounds during 1990.

With the possible exception of extruded PS sheet, prospects for controlling emissions from closed cell foams short of eliminating the services provided by these products are not promising. Recovery and recycle of manufacturing emissions does not appear a workable mandatory control candidate and has virtually no chance of voluntary implementation. Producers of most closed cell foams currently have strong incentives to reduce emissions during normal product use, and the logistics of controlling disposal emissions are formidable. Moreover, CFC use in foam insulation is likely to be insensitive to higher CFC prices, reflecting the value of the energy savings resulting from the use of these highly efficient insulation materials.

For extruded PS sheet, CFC recovery appears a promising voluntary response to higher CFC prices and may be an enforceable mandatory control candidate, although information on this option is currently limited. An alternative option to reduce emissions from PS sheet products is conversion to pentane blowing agents, although such a response may expose workers to fire hazards and may contribute to the creation of smog in urban areas.

# III.D. MOBILE AIR CONDITIONERS

## INTRODUCTION

The air conditioning of automobiles began as a luxury car option in the late 1940s, but is now commonplace. In 1976, nearly three-quarters of U.S.-made passenger vehicles were sold with original equipment mobile air conditioning (MAC) units. Their popularity in light trucks and vans has also been increasing over the last two decades.

An automobile air conditioning system is similar to other refrigeration systems. The refrigerant is contained in a sealed unit. The cooling cycle requires the alternate compression and expansion of refrigerant vapor, with heat being absorbed by the vapor when it expands and being released to the outside environment when the vapor is compressed.

Mobile air conditioning units use R-12 exclusively as the refrigerant. There was a system in the past that used R-22, but its use did not last, presumably because of its higher price and because it requires higher pressures, which make equipment components heavier and thereby reduce auto fuel economy.

Use and emissions of R-12 vary substantially among four major classes of MAC units: (1) original equipment on U.S.-made automobiles; (2) original equipment on imported automobiles; (3) original equipment on light trucks and vans; and (4) aftermarket air conditioners. Overall, IR&T estimates (Burt, 1979) that there were about 64.5 million mobile air conditioners in 1976, and the stock of such units will grow to about 123 million in 1990. The "bank" of R-12 in mobile units, which was 189 million pounds in 1976, is expected to reach 326 million pounds in 1990, reflecting a slight decrease in the average per unit refrigerant charge in the stock of MAC units.

Emissions from MAC units were approximately 76 million pounds in 1976 and might reach 122 million pounds in 1990. These estimates imply an average annual growth rate in emissions of about 3.6 percent compared to a growth rate in MAC stocks of 4.7 percent and a growth rate in the refrigerant bank of 4.0 percent. As described below, the slower projected growth in emissions is due largely to expected reductions in the average initial charge of new MAC units.

All analysis of the future mobile air conditioning use of R-12 is made highly uncertain by the likelihood that automotive designs and sales will be importantly affected by prospective changes in the markets for fuels. The projections for this product area are based on IR&T analyses performed prior to the 1979 petroleum shortages, and should be interpreted in that context.

## USE AND EMISSIONS

The annual U.S. use of R-12 for mobile air conditioners is only partly determined by the number of new domestic units being charged. Some use is for servicing and recharging the stock of air conditioners, including imported units, and some is for replacement of test gas losses and inadvertent emissions during manufacture of the U.S.-made units. To estimate use, therefore, it is necessary first to estimate U.S. installations, U.S. stocks including imported units, and emissions during manufacture and servicing.

## Domestic MAC Production and Stocks

Table 3.D.1 reports the IR&T estimates of historical U.S. original equipment and aftermarket MAC installations. For autos, the share of new vehicles sold with original equipment MAC units rose from about seven percent in 1960 to almost 60 percent in 1970, and had reached 74 percent by 1976. For light trucks and vans, the share of new vehicles with original MAC installations has been lower but is growing rapidly, rising from 30 percent in 1973 to just over 36 percent in 1976. Historically, aftermarket systems were installed only on older cars and trucks, but today some auto dealers install them on new cars because they are cheaper than original equipment systems and can be used to help reduce auto prices at the end of the model year.

Table 3.D.1

U.S. INSTALLATIONS OF MOBILE AIR CONDITIONERS, 1970 TO 1976

(Millions of installations)

| | Original Equipment | | |
|---|---|---|---|
| Year | Autos | Light Trucks and Vans | Aftermarket Sales |
| 1970 | 4.70 | 0.22 | 1.00 |
| 1971 | 4.70 | 0.34 | 1.25 |
| 1972 | 6.00 | 0.49 | 1.40 |
| 1973 | 7.27 | 0.75 | 1.00 |
| 1974 | 5.60 | 0.66 | 1.00 |
| 1975 | 4.88 | 0.64 | 0.75 |
| 1976 | 6.24 | 0.95 | 1.05 |

SOURCE: Burt (1979), Tables 1, 5, and 7. Data have been recalculated and rounded for this presentation.

IR&T used the historical data for autos and light trucks to estimate the parameters of a logistic function describing market penetration by original equipment MAC systems. Those parameter estimates were then used to project future MAC installations from projections of future auto and light truck and van production levels. Increasing market penetration by original equipment systems will limit future growth in aftermarket sales; IR&T estimates that aftermarket sales will average one million per year from 1979 through 1990. Table 3.D.2 reports the estimates of U.S. mobile air conditioning installations for 1977 through 1990.

To estimate annual stocks of mobile air conditioners in the United States, IR&T

### Table 3.D.2

### PROJECTED U.S. INSTALLATIONS OF MOBILE AIR CONDITIONERS, 1977 TO 1990

(Millions of installations)

| Year | Original Equipment | | Aftermarket Sales |
|---|---|---|---|
| | Autos | Light Trucks and Vans | |
| 1977 | 6.94 | 1.04 | 1.40 |
| 1978 | 7.64 | 1.12 | 1.60 |
| 1979 | 7.48 | 1.19 | 1.00 |
| 1980 | 7.88 | 1.29 | 1.00 |
| 1981 | 8.13 | 1.35 | 1.00 |
| 1982 | 8.51 | 1.41 | 1.00 |
| 1983 | 8.12 | 1.23 | 1.00 |
| 1984 | 8.37 | 1.53 | 1.00 |
| 1985 | 8.37 | 1.58 | 1.00 |
| 1986 | 8.41 | 1.64 | 1.00 |
| 1987 | 8.55 | 1.69 | 1.00 |
| 1988 | 8.62 | 1.74 | 1.00 |
| 1989 | 8.77 | 1.80 | 1.00 |
| 1990 | 9.08 | 1.86 | 1.00 |

SOURCE: Burt (1979), Tables 2, 5, and 7. Burt does not estimate future installations in autos. The data shown here were calculated from the data in Table 7 of that report using the formula given on p. 5 of that report. For 1977, the value is assumed to be halfway between the estimates for 1976 and 1978.

uses historical data on U.S. original equipment and aftermarket installations going back to 1960, estimates of MAC equipment on autos imported since 1960, and a model of equipment disposals. The data on imported autos equipped with MAC units are scant; they include data for only some models in two years when 18 percent of the imports had air conditioning. IR&T assumes, lacking better data, that MAC unit penetration of the import car market will grow at the same rates estimated for U.S.-made autos, and that imports will account for 12 percent of the future U.S. auto registrations projected in EPA-supplied data. The disposal function assumes an average life for autos of 10.5 years and an average life for trucks and vans of 14.5 years. Table 3.D.3 lists the resulting estimates of 1976 and 1990 mobile air conditioning stocks in the United States.

The bank of R-12 in mobile air conditioners depends on the stock of units and the average amount of charge. Until recently, the estimated average charge in original equipment units installed in U.S. autos and trucks was 3.8 pounds. Beginning in 1975, Chrysler has been producing units with lower charges and has now completely switched to units requiring only 2.5 pounds, primarily because of system redesign intended to help reduce auto weight and thus improve gasoline mileage.

Table 3.D.3

ESTIMATED U.S. STOCKS OF MOBILE AIR CONDITIONERS, 1976 AND 1990
(Millions of units)

| Type of Equipment/Vehicle | 1976 Stock | 1990 Stock |
|---|---|---|
| Original/U.S. autos | 48.28 | 85.12 |
| Original/imported autos | 2.34 | 6.93 |
| Original/U.S. trucks | 4.72 | 19.93 |
| Aftermarket | 9.16 | 10.83 |
| Total | 64.50 | 122.81 |

SOURCE: Burt (1979), Table 10. Data reported in millions for this presentation.

Aftermarket and imported MAC systems have always tended to use smaller charges because the MAC units themselves are smaller. Assuming the average charge in imported and aftermarket units has always been 2.0 pounds, and taking into account the gradual trend to reduced average charges in the stock of original equipment units, IR&T estimates the 1976 and 1990 bank of R-12 as shown in Table 3.D.4. For 1976, the overall estimated average charge per unit in the stock was 3.44 pounds. The estimated average charge in 1990 is 3.12 pounds.[1]

## Emissions Process

IR&T identifies six sources of emissions: manufacturing and installation, leakage, recharging, repair servicing, accidents, and disposal.

**Manufacturing and Installation Emissions.** R-12 losses are incurred in the leak testing of components, in rework of systems and components that do not meet requirements, during system charging, and from miscellaneous causes associated with small amounts of R-12 ("heels") remaining in drums. Control of these losses is rapidly being achieved by the equipment manufacturers because of the cost savings involved.

The largest manufacturing losses have been in the category of leak testing. Prior to the installation of any controls on this emissions source, perhaps 0.79 pounds per unit was lost in this fashion. The installation of control equipment and changes in the methods of leak testing are markedly changing this picture.[2] IR&T

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[1] We suspect that IR&T's projections for average initial charges for 1980 through 1990 are too high. The market for high mileage vehicles is likely to grow relative to the market for larger, heavier vehicles because of shortages and higher prices for fuels. These trends may not be fully reflected in industry planning, at least during the period when IR&T was collecting its data. Chrysler, for one, is currently suffering financially from a past decision to cut back on downsizing activities. Because MAC charges are partly determined by vehicle design, downsizing could reduce future charges more than IR&T presumes. However, this study has no alternative to the IR&T data.

[2] One control method that has been instituted widely is to learn if units hold a vacuum before using R-12 to determine leakage rates. Another method now implemented by some manufacturers is to use

Table 3.D.4

ESTIMATED U.S. BANK OF R-12 IN MOBILE AIR CONDITIONERS, 1976 AND 1990
(Millions of pounds)

| Type of Equipment/Vehicle | 1976 Bank | 1990 Bank |
|---|---|---|
| Original/U.S. autos | 181.72 | 281.43 |
| Imported/autos | 4.68 | 13.86 |
| Original/U.S. trucks | 17.67 | 66.56 |
| Aftermarket | 18.32 | 21.65 |
| Total | 222.38 | 383.51 |

SOURCE: Burt (1979), Table 12. Data expressed in millions for this presentation. Components may not sum to totals because of rounding.

estimates that these losses will be down to 0.12 pounds per unit by 1980 and that, by 1990, they will be further reduced to about 0.08 pounds per unit.

Manufacturing emissions levels from sources other than leak testing are debated. Industry estimates of the individual sources indicate that, together, they might amount to 4.3 to 16.4 percent of the initial charge. However, Chrysler has provided data from a materials balance calculation for their production facility, which suggest that these losses are 32 percent of initial charge. In the absence of contrary evidence, IR&T used the Chrysler estimate for their 1976 emissions estimates and, assuming there would be some improvements in the future, used 28 percent for the 1990 emissions estimates.

After publication of the IR&T report, Ford provided data from a materials balance calculation for one of its plants, which showed these losses to be closer to six percent of initial charge. However, in previous testimony to EPA, Ford noted that it had already taken actions to improve the design of charging devices, which had reduced charging losses by 25 to 40 percent. This would suggest that the overall average loss aside from leak testing for all manufacturers is somewhere between six and 32 percent. If Chrysler's recent 32 percent loss was exceptional even for that company, as we suspect, overall average losses might be closer to 10 percent. In its sensitivity analysis, IR&T indicates that if the correct figures are 10 percent in 1976 and in 1990, the total manufacturing and installation emissions estimates should be reduced by 42 percent for 1976 and by 60 percent for 1990. The use and emissions estimates reported in this study reflect these adjustments to the IR&T estimates.[3]

**Leakage.** IR&T distinguishes three types of leakage: design, abnormal, and

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mixtures of R-12 with dry air or nitrogen rather than pure R-12 as the test gas. Some manufacturers also recover test gases.

[3] IR&T assumes that aftermarket units have the same manufacturing and installation emissions rates as original equipment units. With regard to imported units, it is assumed that all manufacturing and installation emissions occur overseas, before the units are imported. IR&T notes that some imported cars have U.S.-made (aftermarket) MAC units installed in them, some of which are installed at port of entry. It is unclear from the IR&T documentation whether these units are included in the measure of

excess. Design leakage is what could be expected from a new system that was properly factory tested and had no mechanical or other problems. Abnormal leakage occurs through system malfunction. Excess leakage results from major malfunction or damage and consists of sudden losses of all or most of the charge, leading to immediate repair.

The most commonly mentioned sources of design leakage are hose permeation, compressor seals, gaskets and valves, and fittings. The manufacturers set stringent limits on the leakage permitted during testing in order to reduce warrantee claims and create satisfied customers, and design and materials improvements have reduced design leakage over time. Estimated design leakage was three ounces per year for autos made in the 1966 model year, falling to 2.25 ounces for the 1976 model year, and further falling to 2.1 ounces for the 1990 model year.

Abnormal leakage results from malfunctions that are undetected at the factory or from deterioration, usually at compressor seals, hoses, and metal tubing. The same types of design improvements that reduce design leakage from one model year to the next probably also reduce abnormal leakage, but there is too little evidence from tests of vehicles in operation to judge abnormal leakage rates. IR&T estimates a rate of 1.5 ounces per year from autos in the 1966 model year, dropping to 1.25 ounces for the 1976 model year, and to 1.15 ounces for the 1990 model year.

Autos that are brought in for MAC unit servicing and repair include units that are functioning acceptably but have had leakage sufficient to warrant recharging, units damaged by collision, and units with serious (noncollision) malfunction. IR&T develops a complex model to predict the frequency of repair and servicing for vehicles of different ages, and estimates that excess leakage amounts to 45 percent of the initial charge in vehicles that arrive for servicing for reasons other than simple recharging or repair following accidents.

**Emissions at Recharge.** Servicing simply to replace losses from slow leakage differs from other types of servicing activity in two respects: First, since the unit does not require repair, there may be no need to "open the system up" and release the remaining charge. Second, some consumers recharge their own units with readily available refill cans. On the basis of industry comment, IR&T estimates that units are fully vented at recharge only about 10 percent of the time.

Industry sources agree that the typical leakage loss at which a customer would recognize the need for recharge is about 30 percent of initial charge. Thus, emissions when there is venting at recharge would be about 70 percent of initial charge. IR&T uses its model of servicing frequency to estimate total recharge venting losses in 1976 and 1990.

In addition to venting losses at recharge, there are losses associated with refrigerant transfer, storage, and residuals (heels) left in discarded refrigerant containers. These waste losses are assumed to be 20 percent of the amount of refrigerant used for recharge.

**Emissions at Repair Servicing.** Repairs that require opening up the system

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total aftermarket sales and, if so, whether the estimate of imported MAC units has been properly adjusted to take account of this. In any case, the necessary adjustment in use and emissions to account for this possible error is quite small, and the error would be less great in 1990 data than for 1976 because of a trend toward increased use of foreign-made units in foreign cars. The adjustment reported in the text makes no allowance for the error with regard to imports, and is taken from calculations presented in IR&T's sensitivity analysis.

and venting the remaining charge include replacements of compressors, compressor seals, receiver-drier bottles, hoses, condensers, and evaporators. As indicated above, IR&T's model of frequency of repair predicts the number of vehicles requiring this type of service. The previous estimate that 45 percent of the charge is lost when there is excess leakage in a unit indicates that 55 percent of the charge remains to be vented at service. In addition to venting losses at repair, there are also waste losses like those for recharge servicing.

**Emissions Due to Auto Accidents.** In order to have access to cool air, the condenser in virtually every MAC unit is located directly behind the front grille of the vehicle, where it is vulnerable to damage in head-on collisions. IR&T estimates emissions from this cause by means of a model describing the stock of R-12 in vehicles of different vintages and the probability of a collision that will cause rupture of the MAC unit without leading to immediate vehicle disposal.[4]

**Disposal Emissions.** These emissions equal the number of disposed cars times the amount of charge remaining in each car. The disposal model previously used to estimate stocks by IR&T was used to estimate the number of disposed cars. To determine charge remaining (and thus emissions) at the time of disposal, IR&T assumes that units lose charge gradually over time until recharged, but that half the units over seven years of age are sufficiently deteriorated that they no longer warrant recharge.

### Emissions Estimates

The IR&T emissions estimates, after the adjustment to manufacturing and installation emissions noted above, are shown in Table 3.D.5. The estimates derive from many assumed parameter values that are very uncertain. For example, the sensitivity analysis performed by IR&T suggests the total emissions figure for 1976 could be as low as 46.7 million pounds or as high as 217.6 million pounds.[5]

The "best-guess" estimates in Table 3.D.5 yield an expected result: Original equipment mobile air conditioners in U.S.-made autos are responsible for about three-quarters of annual domestic R-12 MAC emissions. For all types of vehicles, the largest sources of emissions in each year are leakage and repair servicing, which together account for two-thirds of the totals for 1976 and 1990. All types of emissions will grow over the period except possibly manufacturing and installation emissions. In IR&T's emissions model, losses at manufacturing and installation are assumed to be a constant fraction of initial charges, and thus fall as the initial charge declines.[6]

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[4] National Safety Council data show that about 4.5 percent of all accidents are head-on, and insurance data indicate that significant accidents occur within the first three years of life of about 11 percent of all vehicles. Recognizing that some of these accidents will result in disposal rather than repair and that some will not damage the MAC unit, IR&T assumes that 2.5 percent of the stock of units under eight years of age are damaged by collision. For older vehicles, which are less heavily driven and are more likely to be scrapped following collision, the damage rate is assumed to be one percent.

[5] According to the sensitivity analysis for 1990, if all parameters were modified to yield their lowest estimate of emissions, the 1990 level would be negative. IR&T does not explain this peculiar result, but we suspect that it indicates that the sensitivity analysis does not take into account important indirect effects of modifying various parameter values.

[6] Although there is some relationship between initial charges and manufacturing and installation losses, the constant proportionality factor used by IR&T is not based on rigorous analysis. However, even if the 1990 loss estimates are too low, the error is a miniscule fraction of total CFC emissions.

Table 3.D.5

ESTIMATED U.S. EMISSIONS OF R-12 FROM MOBILE AIR CONDITIONERS, 1976 AND 1990
(Millions of pounds)

| Emissions Source | Vehicle/Equipment Type Original/ U.S. Autos | Original/ Imports | Original/ U.S. Trucks | After-market | Total |
|---|---|---|---|---|---|
| | | 1976 | | | |
| Manufacturing & installation | 6.6 | -- | 1.1 | 0.7 | 8.5 |
| Leakage | 17.3 | 1.1 | 1.7 | 2.8 | 22.8 |
| Recharge servicing | 2.2 | 0.1 | 0.2 | 0.8 | 3.3 |
| Repair servicing | 22.1 | 0.8 | 2.2 | 3.0 | 28.0 |
| Accident | 4.3 | 0.1 | 0.4 | 0.5 | 5.4 |
| Disposal | 7.2 | 0.1 | 0.1 | 1.0 | 8.5 |
| Total | 59.6 | 2.3 | 5.7 | 8.9 | 76.5 |
| | | 1990 | | | |
| Manufacturing & installation | 3.6 | -- | 0.7 | 0.1 | 4.5 |
| Leakage | 25.4 | 1.8 | 6.0 | 3.0 | 36.3 |
| Recharge servicing | 2.9 | 0.5 | 1.6 | 0.6 | 4.7 |
| Repair servicing | 30.6 | 2.6 | 7.2 | 2.6 | 43.2 |
| Accident | 6.2 | 0.3 | 1.4 | 0.5 | 8.4 |
| Disposal | 20.5 | 1.0 | 1.8 | 1.7 | 24.9 |
| Total | 89.2 | 6.2 | 18.8 | 8.6 | 122.0 |

SOURCE: Burt (1979), Tables 20 and 21. Manufacturing and installation emissions have been revised downward as explained in text. Data reported in millions for this presentation. Components may not sum to totals because of rounding.

## CFC Use Estimates

Sales of R-12 for mobile air conditioners consist of refrigerant for initial charges of U.S.-made units plus replacement of manufacturing and installation losses, replacement of servicing losses, and recharges at servicing and repair. The IR&T estimates, after the aforementioned adjustment to manufacturing and installation losses, are shown in Table 3.D.6. Because annual servicing use depends on the total stock of units and because repair requires total system recharge as well as leak testing, the repair servicing use is the largest by far, exceeding even the use for initial charges.

### Table 3.D.6

### ESTIMATED ANNUAL SALES OF R-12 FOR MOBILE AIR CONDITIONERS, 1976 AND 1990

(Millions of pounds)

| Purpose | R-12 Sales 1976 | R-12 Sales 1990 |
|---|---|---|
| Initial charge | 28.0 | 38.0 |
| Manufacturing and installation | 8.4 | 4.5 |
| Recharge servicing | 9.1 | 12.4 |
| Repair servicing | 38.0 | 60.0 |
| Replacement of accident losses | 6.3 | 9.9 |
| Total | 89.8 | 124.7 |

SOURCE: Burt (1979), Table 22, adjusted for this presentation as described in text. Components may not sum to totals because of rounding.

## INDUSTRY AND MARKET CHARACTERISTICS

Today's MAC industry in the United States is very large and well established. Annual sales of original equipment alone exceed seven million units and $2 billion. The factories that produce compressors, condensers, evaporators, and accumulators have sizable employment and invested capital, and there have been few (if any) entries or exits to the industry in several years.

The major members of the mobile air conditioning industry are the automobile manufacturers. General Motors employs about 13,200 workers in the production of MAC components alone, and has plants in three locations: Lockport, New York; Dayton, Ohio; and Kokomo, Indiana. The replacement value of the machinery, equipment, and tooling for GM is estimated at $400 million. Ford does not manufacture its own compressors, but does make most of the other components it uses. About 4,500 workers are employed for this purpose in Connersville, Indiana, and Sheldon Road, Michigan. The value of Ford's MAC production capital is about $60 million. For both Ford and GM, the high value of capital investment relative to employment reflects the highly automated design of their MAC production and assembly lines.

IR&T provides little information about Chrysler except to note that it produces a small compressor and uses a system design that requires a smaller initial charge. There is no information about American Motors, but the smaller overall size of that company suggests that it probably purchases some components from independent refrigeration device manufacturers. Two manufacturers who produce compressors for the automakers are York Air Conditioning Division of Borg Warner and Tecumseh Products Company.

The Delco Air Conditioning Division of GM has designed a small, light compressor and has been phasing it into service steadily. As an indication of the long lead times required for retooling when components are redesigned, Delco estimates it will require approximately 10 years for the complete phaseout of their older unit.

Relatively few components are imported, and exports are also minor. For example, out of about seven million compressors manufactured in 1978, less than 200,000 were exported.

IR&T estimates that there are about 140,000 facilities that install and service MAC units in the United States. These range from corner gas stations to specialty shops. Entry into this market appears simple because the required investment is modest and the necessary labor skills are readily available. Given the large number of facilities, it is likely that at least a few hundred thousand individuals are employed by this segment of the industry.

In 1976, the average charge of a newly produced original equipment unit was 3.8 pounds, costing about $1.56. Since the retail price of a mobile air conditioning system is $300 to $700, the refrigerant represents a trivial portion of the final unit price. It appears that few consumers are knowledgeable about the refrigerant needs of their units (the number of pounds they hold, the frequency with which they should be recharged, or the prices of refrigerant). This ignorance may help explain why only about one-third of the units requiring recharge are serviced by their owners, despite the simplicity and low cost of the procedure. Since a MAC unit must be suited for the vehicle in which it is installed, the customer's choice among MAC unit features cannot be made independently of his choice of vehicle. For all these reasons, the refrigerant costs associated with the purchase and servicing of a MAC unit probably have little bearing on the market for the unit.

## OPTIONS TO REDUCE EMISSIONS

IR&T identifies seven options for reducing emissions in this product area. Two of the options, controlling manufacturing and installation emissions and reducing the average initial charge, are already being implemented to some extent by the manufacturers. Further emissions improvements under these options might be achievable. However, data limitations preclude detailed analysis in this study of the economic incentives required to generate further improvements or of the prospective costs of compliance with mandatory controls requiring further improvements. The five remaining options are redesign to reduce leakage, servicing procedure improvements, recovery at salvage yards, conversion to an alternative refrigerant, and conversion to an air cycle system. Some of these options can be induced through economic incentives, but they are poor candidates for mandatory controls because of likely difficulties in enforcement. Others require further technical assessment before they can be evaluated as candidates for regulatory control. The following discussion examines each of the seven options in detail.

## Control of Manufacturing and Installation Emissions

Among the specific emissions-control methods being implemented are transporting units without charge, recovering test gases used during leak testing and rework, pretesting units to see if they hold a vacuum before leak testing, and using mixtures of R-12 with dry air or nitrogen as the test gas rather than using pure R-12. The reported motivation for such emissions controls is the desire to reduce R-12 expenditures at current CFC prices.[7] By 1980, we anticipate that all feasible options will already have been implemented and that further CFC price incentives or mandatory controls would do little to wring further emissions improvement from the manufacturing and installation processes. In any case, these emissions are relatively small, at about 11 percent of total MAC emissions in 1976, and are falling.

## Reducing the Average Initial Charge

In contrast with other refrigeration systems discussed in this report, mobile air conditioner initial charges can be reduced to some extent without complete redesign of all components. Much of the current variation in initial charge from one MAC unit to another is caused by the layout of the system in cars of different model types, with the same compressors and similar evaporators and other components being used in the different models. For example, a reason for differences in charge between two MAC units is the length of hosing required to connect the compressor and evaporator, with longer hoses (and larger initial charges) being required more commonly in larger cars. Component redesign can also help reduce initial charges, but it is very costly to implement and could have a major effect on cooling capability and performance.

Over time, average initial charges have tended to decline. Though the manufacturers achieve some reduction in refrigerant expenses as a result, this is not the primary reason for the change. Instead, the general downsizing of autos to improve fuel economy has indirectly led to system layouts that require less initial charge. In addition, the manufacturers have sought to reduce the weight of MAC units—again in pursuit of better gas mileage—and this has reinforced the tendency for the initial charge to decline.

In principle, it would be possible to institute mandatory controls to require reductions in the average MAC charge in each new fleet of vehicles. Also, since reductions in charge reduce the manufacturers' expenses for R-12, some reduction in charge might be motivated by policies that increase the price of R-12. However, much of the data required to evaluate these policy options are not available. The information we do have is that Chrysler already has a system requiring only 2.5 pounds of initial charge, while two other manufacturers we contacted estimated that average charges could be reduced to 2.5 pounds at a cost of less than $10 per unit, but that further reductions would require retooling.[8] The time required to reduce charges without retooling is unknown; retooling is estimated to require five to seven years to implement. IR&T offers no estimates of retooling costs for the different manufacturers.

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[7] Many observers argue that MAC unit manufacturers would be indifferent to R-12 price increases because the added costs would simply be passed through to vehicle purchasers. This ignores the fact that each MAC producer buys enormous quantities of R-12 each year, and that he can increase his profits substantially if he can reduce R-12 use without changing the price or effectiveness of his MAC units.

[8] One of these manufacturers had previously advised IR&T that reductions below 2.75 pounds would require retooling.

We can be reasonably sure that costs are high enough to preclude retooling in response to CFC prices in the range considered in this study. Redesign without retooling might be induced within the relevant price range, but there is insufficient information to estimate the prices at which various reductions would be induced for different manufacturers. Without this information on retooling costs, the costs of compliance for mandatory controls requiring initial charge reduction cannot be estimated. Available data permit only a calculation of the potential emissions effects of reducing the initial charge.

According to the available information, the minimum average initial charge that could be required for all manufacturers without retooling is 2.5 pounds. Perhaps 20 percent of the current U.S. original equipment units (those produced by Chrysler) will already have an average charge of 2.5 pounds. Suppose, then, that the overall average initial charge for all manufacturers could be brought down to 2.7 pounds by, say, 1983. This would reduce the average initial charge of all new U.S.-made units by a little under 20 percent in 1983 and each succeeding year, and the use of R-12 for initial charges and for replacement of manufacturing and installation losses might fall commensurately.[9] Since manufacturing and installation emissions are quite small already, the reduction in such emissions in 1990 would be only about 0.8 million pounds, and the cumulative reduction between 1983 and 1990 would be less than six million pounds. The effect on emissions from the stock of units would be larger. By 1990, when the units with reduced charges would account for about three-quarters of the equipment stock, the average charge per unit in the stock would be reduced about 12 percent. Disposal emissions would not yet be affected (because almost none of the newer units would be disposed by 1990), but if all other emissions from the stock fell by 12 percent, the reduction in 1990 emissions would be about 11 million pounds. In summary, the cumulative reduction in emissions from the stock between 1983 and 1990 would be less than 40 million pounds. However, the reduction in initial charge would continue to reduce annual emissions after 1990. The full effects of the change would not be observed until about 1995, when nearly all the units in the stock would have been produced after the change.

## Redesign to Reduce Leakage

As noted above, the four most often mentioned sources of design leakage are compressor seals, gaskets and valves, fittings, and hoses. The first of these already appears to satisfy conditions as stringent as are operationally feasible. The second and third sources of leakage are often beyond the manufacturers' control because the performance of gaskets, valves, and fittings is dependent on the care and competence of servicemen in the field where aftermarket units are installed and all units are serviced. The fourth source of design leakage, hoses, appears to be the major source of normal leakage and one where some modifications in materials and design might result in significant reductions in leakage and recharging emissions.

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[9] Based on the IR&T assumption that manufacturing and installation emissions are a function of the initial charge.

The two means by which leakage from hoses might be reduced are use of less permeable hose materials and shortened hose lengths. To some extent, both techniques are already in use. However, most hoses are still made from nitrobutyl rubber and related materials, rather than from metal or other less permeable materials. Reasons given for preferring rubber in this application are that the other materials are stiffer, noisier when the unit is in operation, and more expensive.

There is a serious difficulty in trying to incorporate the option of reduced leakage from hoses in this analysis. The IR&T report indicates that there are substantial unresolved differences of opinion about leakage through hoses under actual operating conditions and therefore about the gains to be achieved by shortening hoses or using different hose materials. There are also insufficient data from which to judge the costs of hose improvements. These questions, together with the more general question of what abnormal leakage is and how best to control it, deserve further analysis, perhaps beginning with empirical studies of refrigerant losses in cars operated under actual conditions.[10] In any case, we cannot attempt to evaluate the implications of mandatory controls to reduce leakage under current conditions of data availability.

It can be noted, however, that reductions in leakage probably cannot be achieved through economic incentives in the form of higher prices for R-12. Reducing leakage during normal use does little to save refrigerant expenses by the manufacturer. While the improvements would save the final consumer some money on recharge expenses, it does not appear that many consumers are sufficiently knowledgeable to take this into account when deciding to purchase a unit. And even the knowledgeable consumer may find that other features of the vehicle he is considering are more important to him than the number of times he will have to recharge his MAC unit.

## Servicing Procedure Improvements

One improvement that would reduce emissions would be to reduce or eliminate venting at recharge. Some service manuals for MAC units recommend venting to avoid buildup of moisture and acid in the system, but the frequency and significance of these problems is unknown. Assuming that MAC unit manufacturers would agree to validate warrantee claims for units that are not vented at recharge, there is still no incentive for the serviceman to retain the existing charge because venting allows him to recharge the entire system at a price that yields him some return over the cost of the refrigerant he uses. It would be virtually impossible to enforce mandatory controls to prevent venting at the thousands of U.S. MAC service facilities. Further, since the customer will probably pay the full cost of a complete recharge without question (at least in the range of CFC prices considered in this study), there is little opportunity to use the economic incentive of higher CFC prices to induce this behavior.

Mandatory recovery of vented refrigerant at recharge or repair servicing would also be virtually impossible to enforce; there are far too many servicemen to monitor, and the customer would be eager to avoid paying the added labor costs and the cost associated with the serviceman's investment in recovery equipment. IR&T estimates that the capital cost alone per pound of recovered (but not reclaimed) refrigerant ranges from about 80 cents to almost $3, depending on the amount of vented R-12 per service facility. These figures make it clear that there would be no market for the recovered refrigerant given a price for virgin R-12 that is under 50 cents per pound. The IR&T estimates do suggest, however, that some recovery might be induced through increased prices for R-12. This is discussed further below.

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[10] Some automakers are already conducting such tests.

Waste losses due to heels in the small cans of refrigerant used by consumers and many servicemen could be eliminated by making such cans illegal. However, emissions might be increased overall because the consumer would then have to take his car in for service, where the remaining charge in the MAC unit has a 10 percent chance of being vented. For this same reason, it is not clear that eliminating the use of small cans by means of economic incentives would be desirable. In any case, emissions from this source are small, amounting to well under five million pounds per year between 1976 and 1990.

## Recovery at Salvage Yards

The disposal emissions estimate counts all losses occurring from the time a vehicle leaves registration. Because there is often a delay between that time and the time a vehicle arrives at a salvage yard, the vehicle often has less charge when it reaches salvage than when it left registration. Industry sources estimate that just 25 to 50 percent of vehicles still have some charge remaining at the time they reach a local salvage yard, and almost none retain a charge by the time they arrive at a central scrapping facility.

IR&T estimates that there are 800 salvage yards, that the average charge remaining when a vehicle reaches such a yard is 40 percent of the initial charge, and that the average facility would currently receive about 2,500 pounds of refrigerant per year.

Salvage yards recover a wide variety of materials from scrapped vehicles, but do not currently recover MAC refrigerant. IR&T remarks that the amount of R-12 available for recovery at the average yard would allow amortization of the investment of $500 to $1,000 for recovery equipment, and suggests that recovery at salvage would occur if there were a market for recovered R-12. In our research concerning other product areas, we interviewed one chemical reclaimer who currently reclaims small amounts of R-12 recovered from other refrigeration devices. While we agree with IR&T that there is no widespread market for reclaimed refrigerant and that there is currently no reclamation of refrigerant from MAC units, we believe the explanation of the failure to reclaim MAC refrigerant lies in a lack of current economic incentives for recovery at salvage.

First, we suspect that salvage yard operators require much more rapid payback of capital investment than IR&T presumes. Whereas IR&T estimates the annualized capital costs at about $200, our estimate would be in the range of $300 to $400, yielding capital costs per recovered pound of R-12 of 12 to 16 cents. Second, IR&T

has no estimate of reclamation costs. On the basis of charges for reclaimed CFC-113 (which is relatively costly to distill), we estimate that a chemical reclaimer would charge approximately 25 cents per pound of reclaimed R-12 before shipping. Purchasers will not pay as much for reclaimed material as they will for virgin refrigerant. Even if they will accept a price differential as little as five cents per pound, and even if shipping costs were zero, the chemical processor would not pay a salvage yard operator more than 11 cents per pound for recovered R-12 given its current virgin price of 41 cents. This would barely cover IR&T's estimate of eight cents for the average capital cost per pound of recovered material, and it would not cover our estimate of capital costs per unit. Finally, IR&T has no estimate of the labor cost for recovery at salvage. Using their assumptions, which imply that the salvage yard would recover only about 1.4 pounds of R-12 at a minimum labor input of five minutes per vehicle, even the low IR&T estimate of capital costs would leave the average salvage yard operator with a return on his labor of about 50 cents per hour. In summary, there appear to be strong economic disincentives for recovery at salvage, given current R-12 prices.

The economic disincentives, together with the difficulty of enforcement, make mandatory controls for recovery at salvage very unpromising. Economic incentives could be established under a policy that increases the price of virgin R-12 as explained below.

### Conversion to an Alternative Refrigerant

Conversion to R-22 is an option that must be mentioned, but which carries with it the necessity for complete system redesign and retooling of the industry, and the energy consequences of a system that is not as efficient and is heavier than present systems. Also, since the pressures of R-22 systems are higher, the emissions would probably exceed R-12 emissions. IR&T provides no data quantifying the costs of conversion, but it is clear that they lie at the farthest extreme of any of the emissions-control options for any product area considered in this study. Morever, since R-22 is currently more costly per pound than R-12, an economic incentive approach to induce conversion would require R-12 prices outside the range considered in this study. Finally, the emissions effects of this option, though substantial in the long run, would be modest before 1990 due to necessary delays in implementation and delays in turnover of the equipment stock.

Conversion to R-142b, a new and experimental refrigerant that is believed to be less hazardous to the ozone than R-12, might hold some promise. However, since this new chemical is not yet commercially available, the implications of conversion to R-142b cannot be assessed in this study.

### Conversion to an Air Cycle System

At the outset of this study, the ROVAC Company was promoting its air cycle refrigeration system as a promising alternative to existing R-12 systems, offering the prospect that all R-12 emissions from MAC units could eventually be eliminated. Now, however, the ROVAC Company no longer sees sufficient promise from this system to continue its development. That company is now beginning to pursue development of an air-vapor system, but it is in too early a stage of development for consideration in this study.

### Summary

The options for controlling emissions from MAC units fall into several analytical categories: (1) Those that deserve further technological or economic assessment but are not sufficiently well understood for detailed evaluation in this study are reductions in initial charge, redesign to reduce leakage, conversion to R-22 or R-142b as the refrigerant, and (possibly) conversion to an air-vapor system; (2) those that might be encouraged by economic incentives but would be difficult or impossible to enforce under mandatory controls are recovery at servicing and at disposal; (3) an option that does not appear promising either under economic incentives or mandatory controls is elimination of venting at repair servicing; and (4) an option that does not appear to warrant policy action because it is already being exploited to nearly its full potential is control of leak testing and installation emissions.

## CFC DEMAND SCHEDULES

Because refrigerant costs are such a small part of MAC unit costs, we can assume that changes in the R-12 price would not affect the demand for mobile air conditioners. As explained above, the only likely response by manufacturers to increased CFC prices in the range considered here would be system redesign to reduce the average initial charge. But as was also explained above, we cannot determine the price at which this response would be induced. Therefore, manufacturing demand for R-12 is treated here as though it is perfectly inelastic. In 1976, the level of R-12 use by the manufacturers was 36.4 million pounds (including amounts used for initial charges plus losses during manufacturing and installation). The average annual rate of growth in manufacturing use through 1990 is estimated to be 1.1 percent, bringing 1980 use to 38.0 million pounds and 1990 use to 42.5 million pounds.

While manufacturing demand is assumed to be unaffected by the price of R-12, a sufficiently high price might induce recovery at servicing. Table 3.D.7 reports the estimated prices of virgin R-12 at which different types of servicing facilities would introduce recovery and the amount of R-12 that would be made available for reuse if each type of facility undertook recovery.[11] Although there do appear to be prices for virgin R-12 that would induce recovery at service, the prices are all well outside the range considered in this study. At prices below $3 per pound of virgin R-12, servicing demand is assumed to be perfectly inelastic. In 1976, servicing use (including all types of servicing) was 53.4 million pounds. Assuming such use grows throughout the future period at an average annual rate of 3.1 percent, 1980 servicing use would be 60.3 million pounds, and would reach the IR&T estimated value of 82.3 million pounds in 1990.

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[11] The calculations assume that (1) the cost of recovery equipment is $1,000 (in 1976 dollars) and that service facilities (which are in a somewhat less volatile business than salvage yards) require equipment payback in five years with future returns from the sale of recovered R-12 discounted at 15 percent per year; (2) growth in the stock of units requiring repair results in proportionate growth in the number of service facilities, maintaining the 1976 distribution of types of facilities; (3) growth in the total amount of R-12 available for recovery is equal to the average annual rate of growth in R-12 use for repair servicing (3.4 percent per year between 1976 and 1990); (4) 75 percent of the R-12 available for recovery is actually returned to use, with 25 percent either being unrecovered because some service facilities of each type have too little R-12 to make recovery worthwhile at any price or because some of the recovered material is lost during handling and reclamation; (5) the average labor cost per recovery operation is $2 (corresponding, for example, with a labor time requirement of eight minutes per vehicle at a charge of $15 per hour); (6) the number of pounds available for recovery per vehicle will be 2.45 pounds throughout the period; and (7) the service facility earns the price of virgin R-12 minus 40 cents for each pound of R-12 it recovers.

Table 3.D.7

EFFECTS OF INCREASED VIRGIN R-12 PRICES ON RECOVERY AT REPAIR SERVICING

| Type of Facility | Number Providing MAC Service in 1976 | 1976 Potential R-12 Recovery Per Facility (lb) | Recovery Inducement Price for R-12 (1976 $) | 1980 Total Reclamation Potential (millions of lb) |
|---|---|---|---|---|
| Service stations | 60,000 | 131 | 4.52 | 6.7 |
| Dealers | 26,000 | 253 | 3.06 | 5.6 |
| Independent repair shops | 45,000 | 156 | 4.04 | 6.0 |
| Fleet shop | 9,000 | 72 | 7.01 | 0.6 |

SOURCE: Burt (1979), Table 19, and calculations explained in the text.

The one remaining way that a change in the price of R-12 might affect its use would be if the price change induced recovery at salvage yards. Assuming that salvage yard operators require a faster payback on recovery equipment than service facilities do, but also require a somewhat lower return on their labor, we estimate that they would find recovery economically rewarding at a virgin R-12 price of about $2 per pound.[12] At that price, the amount of R-12 returned to use in 1980 would be two million pounds, and the amount would grow at eight percent per year through 1990. Since this amount of R-12 would otherwise be vented at salvage, the amount of emissions reduction equals the amount of R-12 returned to use.

In summary, at prices for virgin R-12 below $2 per pound, the combined uses of R-12 for mobile air conditioning would be about 98 million pounds in 1980, and would increase at an average annual rate of 2.4 percent, reaching 125 million pounds in 1990. Emissions would be approximately 87 million pounds in 1980, growing at an average annual rate of 3.4 percent to 122 million pounds in 1990.

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[12] The calculation assumes that (1) the capital cost of recovery equipment is $1,000 (in 1976 dollars) and salvage operators require payback in three years, discounting at 20 percent; (2) the growth in the number of salvage yards is equal to the growth in disposal emissions (eight percent per year); (3) the R-12 available for recovery at salvage grows at the same average annual rate as disposal emissions; (4) 75 percent of the R-12 available for recovery would be returned to use; (5) the average labor cost per recovery operation is $1.50; (6) the number of pounds of R-12 available per vehicle is 1.4 pounds; (7) the salvage yard operator earns the price of virgin R-12 minus 40 cents for each pound of R-12 he recovers.

Assuming, for convenience, that recovered R-12 would be returned to use in mobile air conditioning, a price between $2 and $3 (in 1976 dollars) would reduce 1980 purchases of virgin R-12 to 96 million pounds, and use would then grow slightly faster than two percent per year, reaching 120 million pounds in 1990. At R-12 prices above $2 per pound, 1980 emissions would be 85 million pounds, would grow at an average annual rate of three percent, and reach 118 million pounds in 1990.

## MANDATORY CONTROL CANDIDATES

Two of the options for controlling emissions from mobile air conditioning units, recovery at servicing and recovery at disposal, do not appear to be good candidates for mandatory controls because of the extreme difficulties of enforcing them. A third option, control of leak testing and installation emissions, is already being undertaken, yielding little prospective benefit from mandatory controls. The remaining options, conversion to an air-vapor cycle or to R-22 or R-142b refrigerant and reductions in initial charge, cannot be included in the benchmark for comparison with economic incentive policies because there are insufficient data to evaluate compliance costs. These options would probably have been omitted from the set of benchmark controls in any case because their effects on emissions by 1990 are small relative to their longer-run emissions effects.

Conversion to an alternative refrigerant or to an air-vapor cycle deserves further technical assessment. Either of the options would eventually eliminate emissions of fully halogenated CFCs. Conversion to an air-vapor cycle or to R-22 would impose enormous compliance costs, but conversion to R-142b might not require complete retooling, making it an especially promising option. Since one of these options may eventually prove to be far less costly than the others, and since only one can be chosen for mandatory controls, it is necessary for all three to be thoroughly and simultaneously evaluated.

As noted earlier, reductions in initial charge would impose compliance costs that vary significantly depending on the selection of the charge level. A charge level that would require retooling would not generate large emissions reductions before 1990, and might cost almost as much to implement as any of the conversion options. Hence, it would be wise to consider major reductions in average initial charge simultaneously with the three conversion options. Lesser reductions in initial charge, if they would not require retooling and could be implemented rapidly enough to have a noticeable emissions effect before 1990, might be selected as a mandatory control even if conversion to an alternative refrigerant at a later date remains a possible option. However, the decision to undertake a short-run strategy while continuing to evaluate longer-term solutions to the emissions problem must be weighed against the cumulative costs to consumers (who will pay the total bill for regulation in higher MAC prices). Further research to evaluate those costs is warranted.

## CONCLUSIONS

Mobile air conditioning is currently the largest CFC-using product area and is responsible for nearly one-quarter of 1976 fully halogenated CFC emissions. In

1990, MAC units are expected to remain one of the top three sources of CFC emissions, accounting for just under 20 percent of emissions in that year.

Although the high emissions potential in this product area makes it a desirable target for regulatory control, the control options that would contribute most to reducing emissions—conversion to an alternative refrigerant or to a different refrigeration design—require further technical assessment before their economic implications can be evaluated. This is especially unfortunate because the "bank" of R-12 in MAC units is large (222 million pounds in 1976) and growing (at an average annual rate of nearly four percent per year). Consequently, delay in taking action to reduce R-12 use in this application could have serious implications if the ozone depletion and climate problems prove to be serious. Further technical assessment of options to control R-12 emissions in this product area clearly deserve high and immediate priority.

# III.E. CENTRIFUGAL AND RECIPROCATING CHILLERS

## INTRODUCTION

Chillers are air conditioning systems used in large commercial and industrial buildings.[1] The system consists of a central unit that chills a secondary refrigerant, usually water or brine, which is then circulated to remote units (cooling coils) that cool air. The primary refrigerant used in the central unit varies among R-11, R-12, R-114, R-500, and R-22; of these, the last is excluded from potential regulatory concern under the mandate for this study, but its level of use and its potential as a substitute for other refrigerants remain of interest.[2]

With regard to both emissions and market characteristics, a pertinent distinction is between chillers that use centrifugal compressor designs and those that are reciprocating.[3] While centrifugals rely heavily on R-11 and R-12, reciprocating chillers use R-22. Whereas reciprocating units are used for capacities of 10 to 150 tons,[4] centrifugal units are used for larger capacities, ranging from 75 to 10,000 tons.

### Centrifugal Chillers

The market for centrifugal chillers mushroomed between 1950 and 1964, but has fluctuated around 3,500 units per year since 1965. Exports have been a significant feature of the market, accounting for 30 to 40 percent of total U.S. shipments throughout the recent decade. In the absence of any change in CFC policy, annual domestic shipments are projected to double by 1990; IR&T's projections (see Severn, Cummings-Saxton, and Burt, 1979) presume exports would do the same.

The primary refrigerant in centrifugal units varies. R-11 is used primarily for units under 500 tons capacity, R-12 is used primarily in larger units, and R-114, R-22, and R-500 are used only occasionally in very large units (over 1,000 tons). Overall, R-11 is used in perhaps 80 percent of the units, with R-12 accounting for another 10 percent of the chiller market.

Although early chillers held an average charge of six pounds per ton of cooling capacity, design improvements have lowered that value by half. Consequently, the replacement of older units with the new ones will retard growth in the stock of refrigerant in chillers. The non-R-22 refrigerant stock (or "bank") of 50.8 million pounds in 1976 is expected to reach only 87.8 million pounds by 1990. Similarly, annual non-R-22 emissions are expected to rise only 50 to 60 percent over the period.[5]

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[1] Chillers are occasionally used for industrial refrigeration. Air conditioning accounts for over 95 percent of the market, however, and is the only use considered here.

[2] R-500 is an azeotrope (constant-boiling blend): 73.8 percent R-12 plus 26.2 percent R-152a. Like R-22, R-152a is not considered to be an ozone hazard in this study.

[3] Perhaps 10 percent of the total market is served by absorption chillers that use ammonia or lithium bromide.

[4] Refrigerating systems are traditionally rated in terms of tons of capacity, where one ton refers to the amount of heat required to melt one ton of ice in 24 hours. A ton of cooling capacity corresponds to perhaps 300 square feet of cooling area.

### Reciprocating Chillers

The market for reciprocating units grew rapidly to a peak of nearly 10,000 units in 1966, but has not grown since then, partly due to the recession in commercial construction. Like centrifugal chillers, the reciprocating units are heavily exported; in recent years, about 45 percent of total shipments have been delivered abroad. But unlike centrifugal chillers, the reciprocating units face strong competition from unitary systems (such as heat pumps, which perform both heating and cooling), and so the domestic market is expected to grow only 50 percent by 1990.

Historically, reciprocating units relied exclusively on R-12. In the early 1960s, however, there was a rapid switch to R-22 to improve cooling from compressors of a given size. Because of this switch and the declining market, the bank of R-12 held in reciprocating units is expected to fall from 8.2 million pounds in 1976 to 1.1 million pounds in 1990. Similarly, annual emissions of R-12 should fall from perhaps two million pounds to less than half a million pounds over the period.

## USE AND EMISSIONS

### Centrifugal Chillers

Table 3.E.1 shows annual domestic, export, and total shipments by U.S. makers of centrifugal chillers for the period 1970 through 1976. The ratio of domestic shipments to new commercial floor space in the United States was nearly constant over the period, suggesting that expected growth in commercial floor space could be used to estimate future chiller sales for new buildings. In addition, future sales will include some replacement and rebuilt units that will be reaching the end of their expected lifetimes of 25 years. Table 3.E.2 lists the projections of future domestic installations developed by IR&T according to the foregoing logic.

IR&T does not explicitly report estimated future export shipments. However, IR&T does measure emissions during domestic manufacture of exported units by assuming that exports will continue to add 40 percent to domestic shipments through 1990. By implication, centrifugal export shipments are estimated to rise from 1,261 in 1976 to about 1,974 in 1990.

Annual use (purchases) of CFCs consists of refrigerant used to test units during manufacture and installation, the initial charges for the manufactured units, and refrigerant used in the servicing and recharging of existing units. IR&T computes total use in 1976 and in 1990 (baseline) by adding all emissions in those years—except those associated with chiller disposals—to the amount of CFCs used in

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[5] As explained below, the current and projected levels of non-R-22 emissions are disputed. IR&T estimates them at 12.1 million pounds in 1976, whereas recent data from the Trane Company suggest that the figure is closer to seven million pounds.

## Table 3.E.1

### ANNUAL SHIPMENTS OF CENTRIFUGAL CHILLERS, 1970 TO 1976

(Numbers of units)

| Year | Domestic Shipments | Exports | Total Shipments |
|---|---|---|---|
| 1970 | 2,667 | 1,389 | 4,056 |
| 1971 | 2,718 | 1,275 | 3,993 |
| 1972 | 2,559 | 1,287 | 3,846 |
| 1973 | 2,500 | 1,373 | 3,873 |
| 1974 | 2,893 | 1,601 | 4,494 |
| 1975 | 2,873 | 1,774 | 4,647 |
| 1976 | 1,733 | 1,261 | 2,994 |

SOURCE: Severn et al. (1979), p. 4.

## Table 3.E.2

### PROJECTED DOMESTIC INSTALLATIONS OF CENTRIFUGAL CHILLERS, 1977 TO 1990

(Numbers of units)

| Year | New Construction Sales | Replacement Sales | Rebuilt Units[a] | Total Domestic Shipments[b] | Total Domestic Installations[c] |
|---|---|---|---|---|---|
| 1977 | 1,969 | 59 | (59) | 2,028 | (2,087) |
| 1978 | 2,767 | 116 | (116) | 2,883 | (2,999) |
| 1979 | 2,767 | 150 | (150) | 2,917 | (3,067) |
| 1980 | 2,767 | 183 | (183) | 2,950 | (3,133) |
| 1981 | 2,767 | 222 | (222) | 2,989 | (3,211) |
| 1982 | 3,717 | 239 | (239) | 3,956 | (4,195) |
| 1983 | 3,717 | 270 | (270) | 3,987 | (4,257) |
| 1984 | 3,717 | 292 | (292) | 4,009 | (4,301) |
| 1985 | 3,717 | 327 | (327) | 4,044 | (4,371) |
| 1986 | 3,717 | 372 | (372) | 4,089 | (4,461) |
| 1987 | 4,429 | 411 | (411) | 4,840 | (5,251) |
| 1988 | 4,429 | 462 | (462) | 4,891 | (5,353) |
| 1989 | 4,429 | 491 | (491) | 4,920 | (5,411) |
| 1990 | 4,429 | 505 | (505) | 4,934 | (5,439) |

SOURCE: Severn et al. (1979), p. 11.

[a] The estimate of rebuilt units (given in parentheses) in a given year is equivalent to the number of replacement units; rebuilt units, however, are not included in calculations of domestic shipments.

[b] Total domestic shipments are new construction sales plus replacement sales.

[c] Total installations include new construction sales, replacement sales, and rebuilt units. This total is used to determine chiller stocks and disposals.

charging new, replacement, and rebuilt units.[6] As an aid to later analysis, Table 3.E.3 not only reports total use, but also breaks down the IR&T total figures into: (a) use associated with manufacture and installation, and (b) use associated with field servicing. As explained below, recently available data from an industry source suggest IR&T's field servicing estimates are about three times too high.

### Table 3.E.3

### Use of CFCs for Manufacture and Servicing of Centrifugal Chillers, 1976 and Baseline Projection for 1990

(Millions of pounds)

| Refrigerant | Manufacturing Use | Servicing Use | Total Use |
|---|---|---|---|
| | 1976 | | |
| R-11 | 1.2 | 6.9 | 8.1 |
| R-12 | 0.5 | 2.5 | 3.0 |
| R-500[a] | 0.2 | 1.2 | 1.4 |
| R-114 | 0.2 | 1.0 | 1.2 |
| R-22 | 0.1 | 0.2 | 0.3 |
| Total | 2.2 | 11.8 | 14.0 |
| Total fully halogenated | 2.1 | 11.3 | 13.4 |
| | 1990 | | |
| R-11 | 3.6 | 10.8 | 14.4 |
| R-12 | 1.6 | 3.6 | 5.2 |
| R-500[a] | 0.5 | 1.9 | 2.4 |
| R-114 | 0.5 | 1.5 | 2.0 |
| R-22 | 0.0[b] | 0.4 | 0.4 |
| Total | 6.2 | 18.2 | 24.4 |
| Total fully halogenated | 6.1 | 17.3 | 23.4 |

SOURCE: Severn et al. (1979). Total use is from Table 18, p. 58. Servicing use is the sum of leakage and service-related emissions from the same report, Table 15, pp. 48-49.

[a] R-500 is 73.8 percent R-12 and 26.2 percent R-152a. R-152a contains no chlorine.

[b] Zero due to rounding error. Actual estimate is 22 thousand pounds.

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[6] Few exported chillers are shipped with a charge or with accompanying drums of refrigerant; foreign customers charge the units on arrival using locally available refrigerant. The use figures in Table 3.E.3 reflect test gas emissions during manufacture of exported units but no initial charges for the exported units.

The emissions process for both centrifugal and reciprocating units consists of losses during manufacture, leak testing, reworking, and other production procedures (summed below to yield total manufacturing emissions); losses during shipping and installation; leakage from existing stocks; losses during service of existing stocks; and emissions from disposed units. Here, the discussion concerns these steps in the emissions process for centrifugal chillers.

**Manufacturing Emissions.** During chiller production, manufacturers test condensers, coolers, and compressors for leaks using R-12 combined with dry air regardless of the unit's primary refrigerant. IR&T estimates that the amount of R-12 lost during leak testing and reworking was equivalent to six percent of initial charge capacity in 1976, but will fall to four percent by 1990, largely due to increased recycling efforts.[7]

Despite leak testing, approximately three percent of initial charge is lost inadvertently after units are charged with the primary refrigerant.

**Shipping and Installation Emissions.** Procedures for shipping and installation vary by manufacturer and type of equipment, causing differences in emissions. In summary, IR&T estimates that currently about two percent of the initial charge is lost, and that a trend toward shipping units without charge will reduce this loss to one percent by 1990.

**Leakage During Normal Use.** R-11 machines contain purging systems to remove air and moisture that leak into the unit. These systems are the major source of emissions during normal use, annually releasing 4.2 to 5.5 percent of the initial charge. Maintenance and purging system improvements already under way should reduce both the average loss per purge and the number of purges per year, implying a 1990 annual loss of 3.5 percent of initial charge.

Other leakage sources are pressure relief valves that open whenever excessive pressure builds in the unit, mechanical valves that are used in (high-pressure) R-12 units, lead rupture discs and the carbon discs that have replaced them in newer R-11 units, pipe threads, tube connections, O-rings, gaskets, and flanged joints.

The overall leakage rate is currently 7.5 percent of initial charge per year on average, but will fall to five percent by 1990 largely due to improvements in purge system design and maintenance.

**Service-Related Emissions.** DuPont estimates that 7.8 million pounds of R-11 were sold "to the field" for recharging and servicing centrifugal units in 1976, of which 0.8 million pounds were used at installation of units that were shipped without charge. The leakage estimates developed by IR&T indicate that 2.3 million pounds of the field sales went to replacing leakage, leaving 4.7 million pounds for service-related emissions (i.e., losses associated with all types of servicing and repair activities). The implication of these figures is that 16 percent of the equipment charge capacity is lost each year in servicing, a figure consistent with some industry-supplied estimates.

In a detailed commentary on the IR&T report, the Trane Company disputes these estimates of servicing emissions. The Trane estimate, which is based in part on a survey of refrigerant users and in part on an analysis of servicing losses by type of servicing problem, is that five to six percent of the refrigerant charge is lost during servicing. The argument for this estimate is persuasive, and any future analysis of emissions in this product area might be improved by relying more heavily on the Trane estimates. However, because the Trane data were received only shortly before publication of this report, because they do not seriously jeopardize the arguments concerning control options presented later in this section, and because the IR&T estimates insure against underestimating total CFC emissions and the costs to this industry of regulation, the IR&T results are retained in the analysis developed here.[8]

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[7] One of the three firms described in detail in the IR&T report recovers test gas when testing R-12 and R-500 compressor/heat exchanger units; the recovered gas is reused as a test gas. A second firm recovers test gas only following the final operational test of the chiller. The third firm described by IR&T reports that recovery is not economical at present but should become so by 1990. With increasing chiller production levels and a trend toward heavier use of R-12 and R-500 equipment, in which greater volumes of test gas are required, economic incentives for test gas recovery should improve in the near future.

**Disposal Emissions.** Although one of the three major manufacturers believes that 20 percent of the refrigerant in disposed centrifugal units is recycled, the other two manufacturers disagree and suggest that none is. IR&T averages these estimates to conclude that six percent is recycled. The estimate for disposal emissions reflects this conclusion and the results of a simulation of unit disposals and refrigerant retention at disposal.[9]

Table 3.E.4 reports the IR&T estimates of centrifugal chiller emissions by category and refrigerant for 1976 and 1990. Table 3.E.5 reports the estimated size of the CFC "bank" in centrifugal chillers in 1976 and 1990.

### Reciprocating Chillers

Table 3.E.6 lists domestic, export and total shipments of reciprocating chillers for 1970 through 1976. Market penetration by unitary systems is probably responsible for the decline in domestic chiller shipments since 1969. Regression analysis indicates that the ratio of domestic shipments to new commercial floor space has been declining; the regression results were used by IR&T to predict future new construction shipments from projections of future commercial construction. Assuming that the average lifetime of a reciprocating unit is 20 years, and that only half the retired units will be replaced by new reciprocating units, the total level of future domestic shipments would be as given in Table 3.E.7.[10] As in the case of centrifugals, the export market is expected to add 40 percent to shipments by domestic manufacturers over the foreseeable future.

Refrigerant purchases are computed in the same way for reciprocating units as for centrifugals and may contain the same error for servicing use that was noted above for centrifugal chillers. Since all but two percent of new reciprocating units use R-22, purchases of R-12 are largely for manufacturing leak tests and for servicing and replacement of leakage losses in older units that were designed for R-12. Table 3.E.8 reports IR&T's estimates of CFC use for 1976 and 1990 (baseline).

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[8] Using the Trane estimate of servicing losses would reduce the IR&T figures for total non-R-22 emissions from chillers by six to seven million pounds in 1976 and by nine to 11 million pounds in 1990. Revising the data would reduce the estimates of total non-R-22 emissions from nonpropellant applications by about three percent in 1976 and by about two percent in 1990.

[9] The effects of alternative values for recycling rates are contained in the IR&T sensitivity analysis results reported in the notes to Table 3.E.4.

[10] Reciprocating units are smaller and less costly to replace than centrifugal units, so there is no expectation of a future market for rebuilt units.

## Table 3.E.4

### ESTIMATED 1976 AND 1990 EMISSIONS FROM CENTRIFUGAL CHILLERS BY EMISSIONS SOURCE AND REFRIGERANT

(Millions of pounds)

| Emissions Source | R-11 | R-12 | R-500 | R-114 | R-22 | Total | Total Fully Halogenated |
|---|---|---|---|---|---|---|---|
| **1976** | | | | | | | |
| Manufacturing | 0.06 | 0.21 | 0.01 | 0.01 | -- | 0.28 | 0.28 |
| Shipping and installation | 0.02 | 0.01 | -- | -- | -- | 0.04 | 0.04 |
| Leakage | 2.33 | 0.83 | 0.41 | 0.33 | 0.08 | 3.99 | 3.79 |
| Servicing | 4.60 | 1.64 | 0.82 | 0.64 | 0.16 | 7.87 | 7.50 |
| Disposal | 0.36 | 0.15 | 0.08 | 0.06 | 0.02 | 0.66 | 0.63 |
| Total | 7.37 | 2.83 | 1.32 | 1.06 | 0.26 | 12.84 | 12.83[a] |
| **1990** | | | | | | | |
| Manufacturing | 0.15 | 0.36 | 0.03 | 0.02 | -- | 0.57 | 0.55 |
| Shipping and installation | 0.03 | 0.01 | 0.01 | -- | -- | 0.06 | 0.06 |
| Leakage | 2.73 | 0.92 | 0.46 | 0.37 | 0.09 | 4.57 | 4.36 |
| Servicing | 8.07 | 2.73 | 1.36 | 1.09 | 0.27 | 13.52 | 12.89 |
| Disposal | 1.28 | 0.45 | 0.23 | 0.18 | 0.05 | 2.19 | 2.08 |
| Total | 12.26 | 4.48 | 2.08 | 1.67 | 0.42 | 20.90 | 19.94[b] |

SOURCE: Severn et al. (1979), pp. 48-49; data expressed in millions of pounds and rounded for this presentation. Components may not sum to totals because of rounding.

NOTES: R-152a is a component of R-500. R-22 and R-152a are not treated as ozone hazards in this study.

[a] IR&T sensitivity analysis indicates a possible range for this value of 3.92 to 19.48.

[b] IR&T sensitivity analysis indicates a possible range for this value of 3.25 to 40.02.

The emissions process for reciprocating units is like that for centrifugals, with the following adjustments to the earlier discussion:

(a) Resealing mechanical valves are used in reciprocating machines, almost exclusively.

(b) Whereas shaft seals are not a potential leakage source on centrifugal units because they have an oil reservoir to lubricate the seals during shutdown, the seals on reciprocating machines are not lubricated and will leak under adverse conditions.

(c) The current estimated annual leakage rate of 7.5 percent of initial charge is expected to remain constant through 1990.

### Table 3.E.5

### FLUOROCARBON REFRIGERANT STOCKS IN CENTRIFUGAL CHILLERS, 1976 AND 1990

(Millions of pounds)

| Refrigerant | 1976 | 1990 |
|---|---|---|
| R-11 | 31.1 | 54.5 |
| R-12 | 11.1 | 18.4 |
| R-500 | 5.5 | 9.2 |
| R-114 | 4.5 | 8.1 |
| R-22 | 1.1 | 1.1 |
| Total | 53.3 | 91.3 |
| Total fully halogenated | 50.8 | 87.8 |

SOURCE: Severn et al. (1979), p. 24.

NOTE: R-22 and the R-152a in R-500 are excluded from the total fully halogenated.

### Table 3.E.6

### U.S. RECIPROCATING CHILLER SHIPMENTS, 1970 TO 1976

(Numbers of units)

| Year | Domestic Shipments | Exports | Total Shipments |
|---|---|---|---|
| 1970 | 6,167 | 3,013 | 9,180 |
| 1971 | 6,018 | 3,196 | 9,214 |
| 1972 | 6,244 | 3,189 | 9,433 |
| 1973 | 5,479 | 4,657 | 10,136 |
| 1974 | 6,211 | 4,919 | 11,130 |
| 1975 | 5,222 | 4,030 | 9,252 |
| 1976 | 3,585 | 3,001 | 6,586 |

SOURCE: Severn et al. (1979), p. 15.

The IR&T data on estimated emissions of R-12 and R-22 for 1976 and 1990 (baseline) are reported in Table 3.E.9, as are estimates of the size of the "bank" in the two years.

## INDUSTRY AND MARKET CHARACTERISTICS

The following five companies are the major manufacturers of commercial chiller equipment and account for 90 percent or more of the market:

## Table 3.E.7

### PROJECTED U.S. SHIPMENTS OF RECIPROCATING CHILLERS, 1977 TO 1990

(Numbers of units)

| Year | New Construction Sales | Replacement Sales | Total Domestic Shipments |
|---|---|---|---|
| 1977 | 2,190 | 1,072 | 3,262 |
| 1978 | 2,126 | 1,197 | 3,323 |
| 1979 | 2,067 | 1,347 | 3,414 |
| 1980 | 2,014 | 1,567 | 3,581 |
| 1981 | 2,638 | 1,784 | 4,422 |
| 1982 | 2,577 | 1,966 | 4,543 |
| 1983 | 2,520 | 2,062 | 4,582 |
| 1984 | 2,467 | 2,079 | 4,546 |
| 1985 | 2,417 | 2,038 | 4,455 |
| 1986 | 2,826 | 2,015 | 4,841 |
| 1987 | 2,774 | 1,980 | 4,754 |
| 1988 | 2,726 | 2,021 | 4,747 |
| 1989 | 2,681 | 1,882 | 4,563 |
| 1990 | 2,638 | 1,721 | 4,359 |

SOURCE: Severn et al. (1979), p. 17.

## Table 3.E.8

### USE OF CFCs FOR MANUFACTURE AND SERVICING OF RECIPROCATING CHILLERS, 1976 AND BASELINE PROJECTION FOR 1990

(Millions of pounds)

| Refrigerant | Manufacturing Use | Servicing Use | Total Use |
|---|---|---|---|
| | 1976 | | |
| R-12 | 0.08 | 1.83 | 1.91 |
| R-22 | 0.56 | 2.42 | 2.98 |
| | 1990 | | |
| R-12 | 0.06 | 0.23 | 0.29 |
| R-22 | 0.68 | 3.10 | 3.78 |

SOURCE: Severn et al. (1979), p. 58; data disaggregated by type of use for this presentation.

Table 3.E.9

### ESTIMATED 1976 AND 1990 EMISSIONS AND "BANKED" CFC FOR RECIPROCATING CHILLERS, BY REFRIGERANT

(Millions of pounds)

| Source/Refrigerant | 1976 | 1990 |
|---|---|---|
| Emissions | | |
| Manufacturing | | |
| R-12 | 0.02 | 0.04 |
| R-22 | 0.03 | 0.03 |
| Shipping and installation | | |
| R-12 | (c) | (c) |
| R-22 | 0.01 | 0.01 |
| Leakage | | |
| R-12 | 0.62 | 0.08 |
| R-22 | 0.81 | 1.04 |
| Service-related | | |
| R-12 | 1.22 | 0.16 |
| R-22 | 1.60 | 2.06 |
| Disposal | | |
| R-12 | 0.50 | 0.18 |
| R-22 | 0.05 | 0.68 |
| Total | | |
| R-12[a] | 2.39 | 0.46 |
| R-22[b] | 2.51 | 3.82 |
| The "Bank" | | |
| R-12 | 8.2 | 1.1 |
| R-22 | 10.8 | 13.9 |

SOURCE: Severn et al. (1979), Table 16, p. 52, and Table 14, p. 28.

[a] According to IR&T sensitivity analysis, the possible range for this variable in 1976 is -1.97 to 6.61. In 1990, the range is -.47 to 1.80.

[b] According to IR&T sensitivity analysis, the possible range for this variable in 1976 is -.97 to 5.91. In 1990, the range is 1.07 to 5.00.

[c] Zero because of rounding error. Actual estimates are 200,000 pounds in 1976 and 100,000 pounds in 1990.

Carrier Corporation: Syracuse, New York
Trane Company: LaCrosse, Wisconsin
York Division of Borg-Warner: York, Pennsylvania
Fedders Corporation (Airtemp): Edison, New Jersey
Westinghouse Electric Corporation: Pittsburgh, Pennsylvania

The top three manufacturers employ approximately 30,000 workers; one company reports that 40 percent of its employees are skilled welders who received on-the-job training for this work. All of the companies produce products other than chillers, including other types of air conditioning equipment, and the proportion of company sales and employment attributable to chillers cannot be determined from available data. In addition, an undetermined amount of labor is employed in servicing and installing units in the field.

The major manufacturers produce their own components, including the compressors whose design depends importantly on the type of refrigerant to be used and the initial charge. The investment in production equipment is large, as suggested by a producer's estimate that converting production facilities to use R-22 would cost several million dollars. Since one manufacturer reports that his company runs two shifts five days a week, perhaps the industry could increase chiller supply with the existing capital equipment stock by increasing shifts per day and days per week of production. However, whether this method of expansion is more economical than investing in new capacity cannot be determined from the information given to IR&T.

In recent years, chiller customers have sought reductions in energy utilization. Their willingness to pay up to 15 percent more for chillers with energy-saving features has helped spur design changes that coincidentally lead to reduced initial charges. Customers have also been investing in more heavily insulated structures, causing a trend toward purchases of lower capacity chillers. Thus, reductions in energy use have caused a downward trend in the average refrigerant charge in the stock of chillers.

Some industry sources anticipate a slowing of this trend. Further improvements in energy efficiency now require increased use of low-kilowatt heat exchangers in chillers, and they require larger refrigerant charges for cooling effectiveness. Thus, there now appears to be a technological tradeoff between reduced energy consumption and lower refrigerant charges.

The cost of refrigerant (less than $1,500 even for a very large chiller) is very small relative to equipment costs (which run $30,000 to $60,000 for a unit under 600 tons). Therefore, the domestic market for chillers is probably very insensitive to refrigerant prices. The foreign market for U.S.-made centrifugal chillers would probably also prove insensitive to increasing refrigerant prices if the price increases were worldwide. Moreover, domestic manufacturers would probably not suffer severely in foreign competition with producers in Japan and elsewhere, even if only the U.S. refrigerant price rose, because foreign purchasers typically buy the CFC to charge the American units from foreign suppliers.

## OPTIONS TO REDUCE EMISSIONS

### Test Gas Substitution or Recovery

Together, manufacturing and shipping and installation emissions account for three percent or less of annual chiller emissions in the baseline case for 1976 to 1990. Manufacturers are already reducing these emissions further, partly by improving equipment designs to reduce leakage and reworking losses, partly by shipping units without CFC charge, and partly by recovering test gases. The only remaining options are complete recovery and recycle of test gas or the use of an alternative test gas, such as R-22, nitrogen, or helium.

Presumably R-12 is used because it is less costly than the alternatives, so a change in test gas would increase production costs. Recovery and recycle of test gas, on the other hand, appears to be advantageous to some extent even under current conditions, and is likely to become more cost-saving in the near future as chiller production increases, because a recovery unit then will recover a larger volume of test gas. In fact, given projected increases in centrifugal chiller production, we estimate that at current R-12 prices a firm that requires payback in a period as short as six years should be willing to invest in a recovery unit that costs as much as $15,000 to purchase and 10 cents per pound to operate. Consequently, we expect all the major chiller manufacturers to take advantage of this option in the near future, especially if at least some of the uncertainty about CFC regulation is resolved. If so, mandatory recovery rules would not affect emissions.

Conversion to an alternative test gas might be induced by increased prices for R-12 or required by mandatory controls.[11] Because R-22 is the only specific substitute mentioned by IR&T, the analysis later in this section assumes R-22 is the only substitute test gas to which chiller manufacturers would convert.

### Warning Devices and Maintenance

IR&T speculates that machine leakage during normal use could be reduced by using sniffer detectors and alarm systems to identify leakage problems, and by more systematic maintenance.[12] We are skeptical, in part because we do not believe that customer ignorance of maintenance needs is responsible for the current level of leakage losses. According to IR&T's estimates, a typical service call lasts four days and costs $1,200 and an annual maintenance inspection program would cost about $400 per year. A very large chiller (1,000 tons) loses only 250 pounds per year on average, so even if a warning system could allow the user to prevent all leakage, the cost would be $5.33 per pound of CFC saved, and if systematic maintenance were perfectly effective, the cost would be $1.60 per pound saved. The cost estimates are undoubtedly optimistic because there are losses during the servicing. If the servicing losses were just five percent of initial charge (as estimated by the Trane Company), the net reduction in emissions through these options would be only 65 percent of leakage losses, and the cost per pound of emissions reduction would be 1.6 times the figures given above. In fact, if servicing loss rates are greater than eight percent of initial charge (as IR&T estimates), these options would *increase* emissions. Consequently, unless combined with effective mandatory controls on servicing practices, mandatory controls requiring warning devices or better maintenance would, at best, cause little reduction in emissions and, at worst, might increase them.

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[11] Compliance with such a mandatory control might not be perfect because the manufacturers have several refrigerants in stock for initial charges and could not be constantly monitored to assure compliance. However, the costs of compliance in this case are not extremely high (as indicated later in this section), and there are only a few firms to monitor. Our analysis presumes there would be good compliance despite monitoring difficulties.

[12] The use of dyes to "mark" leaks was criticized by two of the major chiller manufacturers on the grounds that they interfere with compressor operation. We are not able to evaluate this complaint.

### Purge System Redesign

Improvements in purge systems for R-11 machines appear to be an effective way to reduce leakage losses, but IR&T concludes that such improvements are already under way. We speculate that the pressure to improve purge systems comes from customers who are unhappy about having frequent service calls (during which chiller systems are put out of commission for three or four days), and we conclude that mandatory controls are unnecessary. In any case, the emissions effects of purge system improvements are not likely to be very noticeable by 1990 because of the time required for turnover of the equipment stock.

### Initial Charge Reduction

An industry source argues that the fraction of initial charge lost through leakage in units with smaller initial charges would be higher, so they would be serviced more often and annual servicing emissions would be essentially unchanged. Since a reduction in charge would require some component redesign, it could not be done immediately. When accomplished, the change would reduce manufacturing emissions, but these are quite small to begin with, and it would reduce normal use emissions, but only after the new units had replaced a noticeable share of the chiller stock. For these reasons, the change would have only a minor effect on emissions between now and 1990. This option is not considered here as a candidate for mandatory controls.

### Recovery at Servicing

Servicing emissions could be reduced if units were pumped down before servicing, and the recovered refrigerant could be made available for reuse if there were a reliable refrigerant cleanup system to deal with contamination. The economic disincentives for recovery of servicing losses are substantial, however. For a very large chiller, perhaps 500 pounds of servicing losses per year might be prevented through recovery, but this would require an investment of as much as $14,000 for a receiver tank plus added servicing expenses. Using a 10-year payback rule, and ignoring the added service costs, the investment would cost over $2.80 per pound of recovered refrigerant; a similar cost per pound appears likely for smaller chillers, where the receiver tank might cost as little as $3,000 but the amount of potential recovery is less. Given such a disincentive, compliance with a mandatory requirement for recovery would probably be poor, and enforcement at the thousands of user sites would be virtually impossible. And, returning to the earlier commentary on alarm devices and systematic maintenance, the difficulty of enforcing recovery at servicing also indicates that mandatory controls requiring use of those options would have, at best, limited effects on emissions.

### Recovery at Disposal

Recovery with recycle or destruction of disposed refrigerant is an option mentioned by IR&T, with the following comment:

> The significant capital, logistics, and product assurance requirements associated with recovery alternatives weigh against such a procedure in the absence of regulation.

As in the case of recovery at servicing, there appear to be strong disincentives to recover at disposal, and mandatory control would not be effective without enormous enforcement costs. To avoid costly compliance, either the owner or the servicer of the unit can simply vent the system, then claim that no charge remained at disposal. This option is not included here as a candidate for mandatory control.

### Refrigerant Substitution

The final set of options consists of conversion to alternative refrigerants. Reciprocating units are already being displaced to some extent by competitive systems, but reciprocating units now use R-22 and so would not be of concern unless R-22 becomes suspect as a worker health or general climate hazard. With respect to conversion to R-22 in centrifugal units, one manufacturer estimates that the change would take three to four years and $2 million in capital investment per firm for machines under 400 tons; six years and $9 million per firm for machines in the 450 to 2,000 ton range; and three years and $2 million per firm for units over 2,000 tons. In addition, each change would involve substantial engineering costs. Further, the units would be less energy efficient than existing R-11 and R-12 machines.

Lithium-bromide absorption systems once supplied a quarter of the market but are now rarely used because they require five to eight times as much energy to operate and are massive machines when produced in larger cooling capacities. Other types of systems, such as the air cycle and thermoelectric systems, are not currently available as operational systems. Screw-compressor systems are relatively inefficient and have limited capacity; moreover, they are available to new manufacturers only by licensing agreement. Whether and under what economic conditions any of these systems would become viable alternatives to centrifugal chillers is difficult to determine on *a priori* grounds.

## CFC DEMAND SCHEDULES

Because refrigerant costs are a very small source of chiller costs, it is reasonable to assume that the demand for chillers would be unaffected by any change in CFC prices in the range considered here; hence, we assume that chiller output would be unaffected by CFC price changes. The derived demand for CFCs in chillers consists of the demand for manufacture and installation of chillers, and the demand for servicing units in the field. Here we analyze each of these demand schedules for both centrifugal and reciprocating chillers, assuming that R-22 prices remain constant in real terms for the foreseeable future.

## CFC Demand for Manufacturing and Installation of Centrifugal Chillers

According to IR&T data, the average rate of growth in CFC use for initial charges of centrifugal chillers will be about eight percent per year for the period 1976 to 1990. This implies that total refrigerant consumption for charging such units will be about 2.7 million pounds in 1980. Manufacturers inadvertently lose about three percent of the primary refrigerant charge following leak testing, and they lose another one to two percent at installation, bringing 1980 manufacturing use to about 2.8 million pounds. In addition, there is a loss of R-12 during leak testing. This loss might be reduced by means of recovery, or eliminated through substitution of another test gas. As we noted earlier, recovery of test gases appears economic for all the major producers at current CFC prices. Consequently, we assume that there would be as much recovery as possible by 1980, even in the absence of any CFC price increase in real terms. Since there are some losses even with recovery, we assume that there would still be leak testing losses equal to about two percent of the initial charge, or about 0.05 million pounds of R-12 in 1980.[13] Manufacturers could eliminate R-12 test gas losses altogether by substituting R-22 as the test gas, with no change in testing equipment. If R-22 prices remain constant at 64 cents (in 1976 dollars), the switch to R-22 as the test gas would occur if the R-12 price rose 23 cents above its 1976 price of 41 cents. If the price increase occurred in 1980, R-12 emissions would fall by 0.05 million pounds, and R-22 use would increase commensurately.

The only other ways that manufacturers could respond to increased CFC prices would be to reduce the initial charge or convert to R-22 as the primary refrigerant. Manufacturers argue that reducing the initial charge would increase energy requirements, and that chiller purchasers have been willing to pay 15 percent more for chillers that offer substantial energy conservation. Given that refrigerant costs are a small fraction of the purchase price of a chiller, it appears that an enormous increase in refrigerant prices would be required to reverse the tradeoff between energy conservation and equipment costs. We assume the necessary refrigerant price is outside the range of consideration in this analysis (i.e., a marketable permits strategy would not result in prices sufficiently high to induce a reduction in initial charge). Similarly, the very costly conversion to R-22 as the primary refrigerant would not be induced unless CFC prices rose by several dollars per pound. Moreover, reducing the initial charge or converting to R-22 would have little effect on emissions by 1990, because the necessary changes in the manufacturing process would take a few years to accomplish, manufacturing and installation emissions are very small, and a reduction in non-R-22 emissions during equipment use would not become noticeable until the new units replace a substantial fraction of the chiller stock, which would not happen until sometime after 1990.

Manufacturers can reduce overall CFC emissions by improving R-11 purge systems, although there would be no reduction in CFC use by the manufacturer from doing so. As noted earlier, manufacturers are apparently making the needed changes in the purge systems. Purge system improvements are already incorporated in IR&T's baseline estimates of servicing emissions for 1990. We assume here that the changes will have been made by 1980.

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[13] Note that IR&T assumed that leak testing losses would still be four percent of the initial charge even by 1990.

In summary, aside from a miniscule reduction in R-12 use if its price rises to about 64 cents per pound, the manufacturing and installation demand curve appears perfectly inelastic in the price range under consideration here. Table 3.E.10 reports the 1980 level and average annual growth rates to 1990 for manufacturing use at current CFC prices by refrigerant. If the R-12 price rose to 64 cents per pound, annual R-12 use would fall by about eight percent, and R-22 use would rise by the amount of the R-12 reduction.

Table 3.E.10

1980 CENTRIFUGAL CHILLER MANUFACTURING USE OF CFCS AND AVERAGE ANNUAL RATES OF GROWTH TO 1990, ASSUMING CONSTANT REAL CFC PRICES AT 1976 LEVELS[a]

| Refrigerant | 1980 Manufacturing Use (millions of lb) | Average Annual Growth to 1990 (%) |
|---|---|---|
| R-11 | 1.60 | 8.3 |
| R-12 | 0.56 | 9.8 |
| R-500 | 0.27 | 5.8 |
| R-114 | 0.27 | 5.8 |
| R-22 | 0.14 | 0 |

[a] Calculations explained in text.

## CFC Demand for Manufacturing and Installation of Reciprocating Chillers

The IR&T data indicate that only about .04 million pounds of R-12 was used as a primary refrigerant in reciprocating chillers in 1976, and 1990 use will only be about .03 million pounds. An additional .02 million pounds of R-12 was used to leak test reciprocating units in 1976, and only about .03 million pounds will be used for this purpose in 1990. These very small amounts disappear in the rounding error of most of the calculations in this study, and shall therefore be ignored here. The remaining CFC demand for reciprocating chiller manufacture is for R-22, which would not be regulated in the regulatory scenarios considered in this study. Therefore, it is sufficient to note that R-22 use for manufacture of these chillers is projected to grow at an average annual rate of a little over one percent, reaching about .58 million pounds in 1980.

## CFC Demand for Servicing Centrifugal and Reciprocating Chillers

For reasons explained above, there do not appear to be any emissions reductions in servicing that could be induced without imposing a price increase on CFCs of $2.50 or more. Short of such a price increase, the servicing demand schedules are perfectly inelastic. Table 3.E.11 reports estimated servicing use of CFCs for centrifugal and reciprocating chillers in 1980 and average annual growth rates for servicing use to 1990.

Table 3.E.11

1980 CHILLER SERVICING USE OF CFCs AND ANNUAL RATES OF GROWTH TO 1990[a]

| Refrigerant | 1980 Servicing Use (millions of lb) | Average Annual Growth to 1990 (%) |
|---|---|---|
| | Centrifugal Chillers | |
| R-11 | 7.7 | 3.3 |
| R-12 | 2.8 | 2.6 |
| R-500 | 1.4 | 3.3 |
| R-114 | 1.1 | 2.9 |
| R-22 | .2 | 5.1 |
| | Reciprocating Chillers | |
| R-12 | 1.0 | -13.8 |
| R-22 | 2.6 | 1.8 |

[a] Calculations explained in text.

## MANDATORY CONTROL CANDIDATES

As explained above, mandatory controls to assure improvements in R-11 purge systems and recovery and recycle of test gases used in manufacturing centrifugal chillers might be worthwhile. However, unless the admittedly crude evidence is seriously wrong, the mandatory controls would not increase manufacturing costs, nor would they cause emissions reductions beyond those already being induced by current economic conditions. The only remaining mandatory controls that appear feasible and effective would be conversion to R-22 as a test gas and/or as the primary refrigerant in centrifugal chillers.

Conversion to R-22 as a test gas would increase manufacturing costs by 23 cents per pound of test gas. In 1980, the total cost (in 1976 dollars) would be about $11,500 for centrifugal chiller manufacturers and about $4,600 for reciprocating chiller manufacturers. The total cost would increase in real terms by about eight percent per year for centrifugal chillers and about one percent for reciprocating chillers, as the number of chillers being tested increases. The average cost increase per chiller would be well under $5, all of which would presumably be passed on to chiller purchasers, both in the United States and abroad.

The conversion to R-22 test gas would reduce 1980 emissions of R-12 by 0.07 million pounds (0.05 million pounds for centrifugals manufacture and 0.02 million pounds for reciprocating manufacture). In 1990, the R-12 emissions reduction would be 0.14 million pounds (0.11 million pounds for centrifugals alone). Assuming the mandate is implemented in 1980, the cumulative reduction in R-12 emissions would be 0.8 million pounds for centrifugal chillers and 0.2 million pounds for reciprocating chillers, for a total reduction of 1.0 million pounds. The cumulative cost to centrifugal manufacturers, discounted at 11 percent, is about $110,000. For reciprocating chiller manufacturers, the cumulative cost is about $33,000.

Conversion to R-22 as the primary refrigerant in centrifugal units appears so costly that it is not used in this study to form the benchmark emissions reduction for comparing mandatory controls with economic incentive policy strategies. As described above, investment costs alone would run from $2 to $9 million (depending on chiller size) for each manufacturer. Assuming that the requirement would be announced in 1980, that it would go into effect in 1985, and that at most five percent of the chiller stock is replaced each year, the maximum emissions effect that could be achieved by 1990 would be only about five million pounds. Of course, the emissions effect would increase thereafter, but non-R-22 emissions would not be completely eliminated until after the year 2000.

## CONCLUSIONS

As of 1976, chillers of all kinds were responsible for only about four percent of total emissions of fully halogenated CFCs in the United States. By 1990, chillers' share of emissions is expected to decline slightly, to under three percent. There are few options for reducing emissions that are not exceedingly costly to implement and that would not pose severe enforcement problems if required under a mandatory control strategy. In comparison with other product areas, regulatory action toward chillers would have little effect on emissions.

# III.F. HOME REFRIGERATORS AND FREEZERS

## INTRODUCTION

The only CFC refrigerant used in home refrigerators and freezers is R-12.[1] Although freezers require 50 percent more refrigerant per unit than refrigerators, the technologies and functional characteristics of the two types of units are similar. The refrigeration cycle occurs in a hermetically sealed system; it consists of compression of R-12 gas, cooling to convert the gas to a liquid, and expansion to allow evaporation of the liquid. During evaporation, the R-12 absorbs heat from the refrigeration unit and then returns to the compressor to renew the cycle.

Two different types of compressors are used in refrigerators and freezers today. About half of the manufacturers produce units containing rotary compressors. The remaining manufacturers use reciprocating compressors, which require one-third to one-half the refrigerant charge of the rotary compressors for the same type of refrigeration appliance.

Prior to 1931, refrigerants such as methyl chloride, ammonia, and sulfur dioxide were employed in all refrigeration equipment. Since these materials are toxic—and some are also flammable or explosive—their safety for use in the home has been questioned. R-12 is nontoxic, nonflammable, and nonexplosive. At least since 1946 (the earliest date in the data for this product area), R-12 has been the only refrigerant used in home refrigerators and freezers.

Refrigerator sales in the United States are currently running about five million units per year. This market is approximately saturated now, so most future growth will be due to an increase in the number of households. Domestic sales are projected to increase only to about eight million units by 1990. Refrigerator exports and imports are a small fraction of domestic sales.

Freezer sales fluctuated around an annual average of about one million units until 1965. Between 1965 and 1975—a period of rapid increases in meat prices—average annual freezer sales in the United States more than doubled. Freezer imports contributed to this growth, rising from seven percent of domestic sales in 1965 to 17 percent in 1976.[2] IR&T anticipates market retrenchment from the recent growth spurt, with sales fluctuating around two million units over the next decade and reaching 2.3 million units in 1990 (see Cummings-Saxton, Severn, and Burt, 1979).

The "bank" of R-12 in refrigerators and freezers is projected to grow rather slowly, from 85.7 million pounds in 1976 to 104.1 million pounds in 1990. Annual refrigerant emissions are expected to increase slowly from five million pounds in 1976 to seven million pounds in 1990.

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[1] This section does not analyze the use of CFC-11 to insulate refrigerators and freezers, which is covered in Sec. III.D. This section also omits the use of R-12 in other small home appliances, such as dehumidifiers, water coolers, and ice machines. Section III.H examines dehumidifiers. Data on the other two small appliances are too scant to permit analysis.

[2] Freezer exports have always been few.

When placed in the context of the other CFC uses studied in this report, home appliances appear to be unimportant, both as sources of emissions and (therefore) as targets for regulatory action. Nevertheless, in the policy debate over protection of the ozone layer, home appliances are frequently held up as an example of highly valued consumer products that might be endangered by policies to restrict CFC emissions. To address this concern, the home appliance product area has received detailed attention in this research.

## USE AND EMISSIONS

Data from IR&T on domestic shipments, exports, imports and domestic sales of refrigerators and freezers for 1970 through 1976 are presented in Table 3.F.1. Table 3.F.2 reports domestic sales of refrigerators and freezers as projected by IR&T from a model describing growth in numbers of households, increases in market saturation, and replacement of discarded devices.

Table 3.F.1

ANNUAL REFRIGERATOR AND FREEZER SALES, 1970 TO 1976

(Thousands of units)

| Year | Domestic Shipments | Imports | Exports | Domestic Sales |
|---|---|---|---|---|
| | | Refrigerators | | |
| 1970 | 5,259 | 595 | 117 | 5,737 |
| 1971 | 5,544 | 787 | 118 | 6,213 |
| 1972 | 6,069 | 901 | 121 | 6,849 |
| 1973 | 6,527 | 641 | 223 | 6,945 |
| 1974 | 5,707 | 311 | 388 | 5,630 |
| 1975 | 4,553 | 409 | 278 | 4,684 |
| 1976 | 4,912 | 506 | 328 | 5,090 |
| | | Freezers | | |
| 1970 | 1,305 | 340 | 15 | 1,630 |
| 1971 | 1,241 | 448 | 13 | 1,676 |
| 1972 | 1,355 | 514 | 12 | 1,857 |
| 1973 | 2,287 | 366 | 19 | 2,634 |
| 1974 | 3,061 | 178 | 28 | 3,211 |
| 1975 | 2,645 | 233 | 30 | 2,848 |
| 1976 | 1,483 | 288 | 36 | 1,735 |

SOURCE: Cummings-Saxton et al. (1979), Table 1, p. 4 and Table 5, p. 11.

By 1976, market saturation of refrigerators was 106 percent. The sales projections are based on the assumption that this relationship between households and refrigerator stocks will obtain through 1990. In contrast, 1976 market saturation by freezers was estimated at 44 percent. On the basis of the historical growth rate

## Table 3.F.2

### PROJECTED DOMESTIC REFRIGERATOR AND FREEZER SALES, 1977 TO 1990

(Thousands of units)

| Year | Refrigerators | Freezers |
|---|---|---|
| 1977 | 5,004 | 1,800 |
| 1978 | 5,001 | 1,939 |
| 1979 | 5,217 | 2,040 |
| 1980 | 5,572 | 1,952 |
| 1981 | 5,968 | 1,970 |
| 1982 | 6,324 | 1,993 |
| 1983 | 6,489 | 1,954 |
| 1984 | 6,633 | 1,996 |
| 1985 | 6,842 | 2,123 |
| 1986 | 6,931 | 1,953 |
| 1987 | 7,225 | 1,956 |
| 1988 | 7,641 | 1,973 |
| 1989 | 8,081 | 2,165 |
| 1990 | 7,959 | 2,305 |

SOURCE: Cummings-Saxton et al. (1979), Table 3, p. 8, and Table 7, p. 15.

for the period 1948 to 1976, IR&T estimates that market saturation for freezers will increase to 54 percent by 1990. The disposal functions used by IR&T assume mean lifetimes of 17 years for refrigerators and 20 years for freezers.

The stocks of R-12 contained within refrigerators and freezers depend on both the sales of new units and disposals. Table 3.F.3 lists the numbers of refrigerators and freezers and their R-12 stocks for 1976 and 1990. The table indicates that the "bank" of R-12 is expected to increase by 21 percent between 1976 and 1990.

## Table 3.F.3

### DOMESTIC REFRIGERATOR AND FREEZER STOCKS, 1976 AND 1990

| | Refrigerators | | Freezers | |
|---|---|---|---|---|
| Year | Thousands of Units | Millions of lb of R-12 | Thousands of Units | Millions of lb of R-12 |
| 1976 | 87,173 | 54.5 | 33,328 | 31.2 |
| 1990 | 103,974 | 65.0 | 41,720 | 39.1 |

SOURCE: Cummings-Saxton et al. (1979), Table 4, p. 9, Table 8, p. 14, and Table 9, p. 18.

Annual use of CFCs includes the R-12 used to test units during manufacture, the initial charges for new units, and replacement of the R-12 that is lost through leakage and during servicing. Two factors important in determining initial refrigerant charges are the size of the refrigeration unit and its compressor design. A larger quantity of refrigerant is necessary in larger units, and rotary compressors require more refrigerant than reciprocating compressors. The average charge per refrigerator is estimated at 10 ounces, with 50 percent of the units (those using reciprocating compressors) having a five-ounce average charge, and the other 50 percent (those using rotary compressors) having a 15-ounce average charge. The average freezer charge is estimated at 15 ounces, again assuming half the units have an average charge of 10 ounces, and the other half, 20 ounces. IR&T computes total use by summing R-12 use in charging new units and all R-12 emissions except those from disposal. The total estimated R-12 use in 1976 and 1990 for refrigerators and freezers is shown in Table 3.F.4.

Table 3.F.4

DOMESTIC R-12 USE IN REFRIGERATORS AND FREEZERS, 1976 AND 1990

(Millions of pounds)

| Year | R-12 Use | | Total |
|---|---|---|---|
| | Refrigerators | Freezers | |
| 1976 | 4.233 | 2.030 | 6.263 |
| 1990 | 6.423 | 2.976 | 9.399 |

SOURCE: Cummings-Saxton et al. (1979). Data recalculated to correct errors found in the results in Table 11, p. 31 of that document.

Four categories of refrigerant losses can occur over the lifetime of a refrigerator or a freezer: manufacturing, leakage, service, and disposal losses.

### Manufacturing Emissions

The leading manufacturers of refrigerators and freezers manufacture their own equipment components. Emissions from the manufacturing process include losses that occur during leak testing of components, system charging, and rework of defective systems.

Most components are first leak tested with high pressure air in a water bath to identify gross leaks, then with either R-12 or helium to identify minute leaks. Although the traditional testing method uses R-12 as the test gas with a halide "sniffer" detection device, one manufacturer has employed helium test gas with mass spectrometry detection for nearly 30 years. Not coincidentally, this same manufacturer produces and sells the helium system as a separate product line.

Recovery systems to capture R-12 test gas are increasingly being adopted by appliance manufacturers. IR&T estimates that in 1976, overall industry R-12 releases associated with component testing were 1.5 percent of initial charge, but that it will fall to 0.5 percent by 1990 largely due to increased use of R-12 test gas reclamation systems.

One large manufacturer, General Electric, estimates that an additional 1.5 percent of the refrigerant charge escapes from the charging connection during refrigerant charging. IR&T assumes this percentage applies for other manufacturers as well, and that it will remain constant through 1990.

After assembly and charge of the unit, "sniffer" leak tests are performed at critical joints. The units are then passed through a simulated refrigeration-cycle test. If a component is not functioning properly, it is replaced. One industry source estimates refrigerant losses during system rework at five percent of the charge, with recovery not currently practiced.

Summing the losses from each manufacturing stage yields losses of eight percent of the initial charge for both refrigerators and freezers produced in 1976; for 1990, the figure is seven percent.

### Leakage During Normal Use

Testimony by an industry trade association[3] indicates that normal use leakage losses are less than one percent of initial charge in a five-year period. General Electric has estimated that leakage losses are less than two percent in 15 years. IR&T assumes an industrywide annual leakage rate of 0.2 percent of the existing stocks for refrigerators and freezers for 1976 through 1990.

### Servicing Emissions

High design and test standards in manufacturing make appliance breakdowns rare, with many units never being repaired over their lifetimes. When repairs are needed early in a unit's life, they usually involve excessive noise but occasionally they can result from serious leaks at joints. Later, problems associated with moisture buildup and restricted flow predominate, and compressor failures become the cause of a large percentage of the service calls. If the refrigerant becomes contaminated when the compressor fails, the serviceman releases the refrigerant, installs a new compressor, condenser, and service dryer, and purges the system, releasing about three ounces of refrigerant overall. From warranty records and conversations with industry sources, IR&T estimates the annual servicing release rate at 1.5 percent of refrigerant charges in the stocks of refrigerators and freezers for 1976 through 1990.

### Disposal Emissions

Potential refrigerant releases during appliance disposal are equal to the initial charge minus unreplaced leakage during normal use. Assuming a 0.2 percent leakage rate per year, a typical refrigerator will lose 3.4 percent of its charge without replacement over its lifetime of 17 years. Therefore, at disposal, the typical refrigerator contains 96.6 percent of its original charge. The average freezer with a lifetime of 20 years will retain 96 percent of its original charge.[4]

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[3] Weizeorick (1977).

Actual disposal emissions depend on what happens to refrigerators and freezers at disposal. Although it has been assumed here that disposal emissions occur in the year the appliance is disposed, this may not be the case. The charge could be emitted gradually over many years if the appliance were disposed intact, say by burial in a landfill site.

### Total Emissions

Total emissions from refrigerators and freezers for 1976 and 1990 are given in Table 3.F.5. Emissions during manufacture are prompt, while all other losses are from the existing stock or the "bank" of R-12 in the appliances. The largest source of emissions in both 1976 and 1990 is disposal.

## INDUSTRY AND MARKET CHARACTERISTICS

IR&T identifies seven refrigerator and freezer manufacturers, with 12 plants in all. The firms are:

1. General Electric, the largest manufacturer, with four plants.
2. Whirlpool, with three plants.
3. Admiral, with one plant.
4. Amana, with one plant.
5. Frigidaire, with one plant.
6. Revco, with one plant.
7. White Industries, with one plant.

The *1972 Census of Manufactures* indicates that in 1972 there were 36 manufacturers of refrigerators and freezers in the United States, with 34,000 total employees. Of the 36 firms, 20 are located in the North Central region, six in the South, six in the Northeast, and four in the West. Some or all of these firms may produce other products in addition to refrigerators or freezers. Twelve of the companies have 1,000 employees or more and account for more than 90 percent of the total value of shipments.

We have no data on the value of the capital stock in this industry, but comparison with the other refrigeration product areas suggests it is surely in the tens (if not hundreds) of millions of dollars.

Prices of refrigerators and freezers vary widely depending on capacity and design, but R-12 is not likely to be a significant cost feature in even the cheapest units. At the 1976 R-12 price of 41 cents per pound, the cost of refrigerant for a freezer requiring as much as 22 ounces of charge only amounts to 56 cents.[5]

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[4] IR&T estimates that 30 to 35 percent of the charge must be lost before detection. Therefore, it is reasonable to assume that losses of 3.4 to 4.0 percent over the lifetime of the unit would not be replaced.

[5] The price of R-12 at retail to a home appliance owner could be several times the price given here without affecting the conclusion reached in the study.

## Table 3.F.5

### APPLIANCE REFRIGERANT EMISSIONS BY CATEGORY, 1976 AND 1990

(Millions of pounds)

| Operational Phase | Refrigerators | Freezers[a] | Total |
|---|---|---|---|
| | 1976 | | |
| Manufacturing | .238[b] | .106[b] | .344[b] |
| Leakage | .109 | .063 | .172 |
| Service | .816 | .471 | 1.287 |
| Disposal | 2.310 | .884 | 3.194 |
| Total | 3.473[b] | 1.521[b] | 4.994[b] |
| | 1990 | | |
| Manufacturing | .344[c] | .148[c] | .492 |
| Leakage | .130 | .078 | .208 |
| Service | .975 | .589 | 1.564 |
| Disposal | 3.613 | 1.580 | 5.193 |
| Total | 5.062 | 2.395 | 7.457 |

SOURCE: Cummings-Saxton et al. (1979), Table 10, p. 28, unless otherwise indicated.

[a] The values for 1990 in this column have been recalculated to correct errors in the IR&T report.

[b] This value has been recalculated to correct an error in the IR&T report.

[c] Manufacturing emissions for 1990 were calculated by IR&T on the basis of projected domestic sales, and therefore omit domestic manufacturing emissions for exported units and include foreign manufacturing emissions for imported units. The IR&T report does not provide projections of exports and imports, so this error could not be corrected for 1990 as it was for 1976. The error would probably be small for refrigerators but could be large for freezers. Refrigerator imports have generally been very small units, and exports and imports may compensate one another. In contrast, the number of freezers imported has been far larger than the number exported in recent years, so the error for 1990 could be large.

Because refrigerant is a miniscule fraction of appliance costs, neither the domestic nor the foreign market for refrigerators and freezers is likely to be sensitive to R-12 price increases, even if only the U.S. price rose.

## OPTIONS TO REDUCE EMISSIONS

IR&T identifies six methods for reducing emissions from home refrigerators and freezers: (1) helium leak testing at manufacture; (2) recovery at rework; (3) recovery of losses at servicing; (4) recovery at disposal; (5) use of only reciprocating compressors in new appliances; and (6) substitution of R-22 for R-12.

### Helium Leak Testing

Traditionally, home appliance manufacturers have used R-12 to leak test components and systems. However, General Electric, which performs perhaps a third of all leak testing, uses helium for this purpose. And IR&T reports that others are making the conversion.

The economic implications of using helium rather than R-12 depend on the cost of the helium testing system, the amount of R-12 that can be saved per plant, and the cost of the helium itself. We estimate that the mass spectrometer and vacuum system required for helium testing costs under $35,000. The cost of the helium itself is unknown to us, but it is likely to be very small because the amounts used per appliance are miniscule. Since IR&T did not obtain data on appliance output per plant, we cannot assess the potential savings in R-12 leak testing expenses from conversion to a helium system.

If we assume that testing losses are proportional to initial charges of reciprocating and rotary units and that each of the 12 manufacturing plants produces an equal share of final output, we find that rotary manufacturers would find helium leak testing cost-saving at current R-12 prices.[6] Under the same assumptions, reciprocating unit manufacturers would find helium cost-saving at a substantial increase in R-12 prices (to about $1.25 per pound from the 1976 price of 41 cents). However, this analysis may be misleading because the two assumptions could be wrong. General Electric, for example, apparently finds helium leak testing cost-effective at current prices for R-12 even though GE produces reciprocating units that have relatively low R-12 leak testing loss rates.

Without detailed data on final product output and testing losses per rotary and reciprocating plant, we cannot properly assess the net costs to firms of using helium test systems. We can be certain, however, that the emissions effects of such a change would be very small. IR&T estimates that leak testing losses are currently less than 20 percent of manufacturing losses, and the leak testing share is declining.

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[6] The analysis also assumes that the manufacturers project market growth rates similar to those estimated by IR&T, and make investment decisions by assuming a 10-year equipment payback period and discounting future R-12 savings at 12 percent per year.

With manufacturing losses running under half a million pounds per year, complete conversion to helium leak testing from 1980 on would yield at most a cumulative reduction in R-12 emissions by 1990 of only a little over one million pounds.

Since helium testing would reduce manufacturers' purchases of R-12, it could probably be induced by a sufficiently high price for R-12.

Helium testing might also be a feasible candidate for mandatory control. Enforcement would involve making sure that each firm has the necessary equipment —provided the cost of using the unit does not exceed the cost of using R-12—which seems likely since one manufacturer already uses a helium system. Unfortunately, although we have an estimate of the required capital cost of compliance, we cannot estimate the necessary inducement price of R-12 or net cost of compliance with mandatory controls without data on operating costs and potential R-12 savings per plant.

## Recovery at Rework

The R-12 that is currently discharged to the atmosphere during rework could be recovered and reused. Although the recovered R-12 may not be pure enough for charging new appliances, it might be usable for rework testing without reclamation.

IR&T estimates the capital cost of a recovery unit at $50,000 to $100,000. Operating costs for using the equipment are unknown, but probably small, consisting largely or entirely of the cost of a few minutes of labor time. If we assume that each plant is responsible for one-twelfth of the rework losses estimated by IR&T, and if we assume operating costs are zero and the capital cost is $75,000, then recovery at rework would be cost-saving at current R-12 prices for each plant.[7] Taking into account that rotary manufacturers have larger rework losses per appliance than reciprocating manufacturers, but that reciprocating plants may produce a larger share of final output, recovery at rework still appears cost-effective for most plants.

We suspect that IR&T's estimate of losses at rework are much too high. This would help explain why firms do not recover at rework despite the appearance that it should be cost-effective. It would also help explain why several firms are recovering R-12 test gas losses and yet are not recovering losses at rework. A possible explanation for the high estimate by IR&T might be that they properly estimated the loss rate per reworked appliance, but failed to consider that few appliances require rework. In any case, we cannot explain why recovery at rework is not practiced if IR&T's loss estimates are correct.[8]

In principle, recovery at rework might be induced by a sufficiently high price for virgin R-12. Mandatory recovery at rework might be a feasible control option, depending on whether the cost of using a recovery unit once it is purchased is covered by the savings from reduced purchases of virgin R-12. If not, monitoring to assure that firms actually use the equipment would be extremely difficult.

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[7] According to IR&T, rework losses are about 60 percent of manufacturing losses, which currently run about .5 million pounds per year for all plants combined.

[8] We can be sure, however, that recovery at rework, even if universally practiced, would have little effect on CFC emissions. Even if IR&T's estimates are correct, the cumulative emissions reductions by 1990 under full recovery from 1980 on would be only a little over three million pounds.

### Recovery at Service

To recover servicing losses, each serviceman would have to carry a portable recovery pump and tank which IR&T estimates would cost $1,000. Assuming the recovery process would take between 10 and 20 minutes at a labor charge of $30 per hour, the labor cost of recovery would be $5 to $10 to recover a few ounces of R-12 per service call. Labor costs alone would thus be several dollars per pound of recovered R-12, and there might also be reclamation costs of perhaps 25 to 35 cents per pound of recovered refrigerant.

These high compliance costs, which make evasion profitable to servicemen and their customers, together with the large number of servicing sites and occasions, would make enforcement of mandatory recovery at service virtually impossible. Even if the serviceman were required to purchase the recovery unit, there are strong incentives for him not to use it.

### Recovery at Disposal

There are no data on what happens to refrigerators and freezers at disposal. For recovery at disposal, central collection points for the disposed appliances would have to be identified. It would be virtually impossible to enforce a requirement for people to have their disposed appliances delivered to the collection point; and a financial incentive would probably have to be several dollars per appliance.

### Use of Only Reciprocating Compressors in New Appliances

Using a reciprocating rather than a rotary compressor in a new refrigerator or freezer reduces the charge, on average, by about five ounces. Over the life of the appliance, the change reduces R-12 emissions from a refrigerator by about 50 percent and reduces emissions from a freezer by about 30 percent. If half of all refrigerators and freezers (both new and existing) are made with rotary compressors, a change in manufacturing to eliminate the use of rotary compressors would eventually reduce annual emissions of R-12 by 30 to 40 percent.

An IR&T researcher has estimated that retooling the portion of the industry that currently uses rotary compressors would cost over $20 million and take two to four years to accomplish. It is not clear, however, that such retooling would actually occur. If reciprocating unit manufacturers have sufficient capacity to supply a larger share of the market than they currently do, some or all of the existing plants that made rotary compressors might cease production altogether rather than undertake the cost of retooling. The data provided by IR&T do not permit us to assess the likelihood of this event.

### Substitution of R-22 for R-12

Eliminating the use of R-12 in home appliances would eventually eliminate emissions of fully halogenated CFCs from this product area. IR&T estimates the cost for the industry as a whole to make this conversion at $140 million, and the time required to make the change at five to seven years. The full effect of the change on R-12 emissions would not be achieved until sometime after the year 2000, because the existing stock of R-12 appliances is very long-lived. In addition, there might be an energy penalty from the use of R-22 units.

### Summary

Of the six emissions control options mentioned by IR&T, four would be feasible and effective as candidates for mandatory controls. Two of these, helium leak testing and recovery at rework, would impose rather modest costs on industry but would have very small effects on emissions. The other two, use of reciprocating compressors exclusively in new appliances and substitution of R-22, would generate larger emissions improvements, at least in the long run, but are far more costly. The two control options that are not good candidates for mandatory controls because of the difficulties of enforcing them are recovery at service and at disposal. These two options would also be far too costly to induce by raising prices for R-12, at least within the price range considered in this study.

## CFC DEMAND SCHEDULES

The preceding discussion outlines four ways in which the home appliance manufacturers could reduce their use of R-12. Two of the options might be induced by prices that are not much above the current price of R-12. These options are helium leak testing and recovery at rework. In both of these cases, however, we are unable to estimate the R-12 inducement price because of inadequate data on the level of R-12 losses per plant. A third option, exclusive use of reciprocating compressors, applies only to rotary unit manufacturers. The price at which this option would be induced cannot be determined without data on output level per plant and capacity of reciprocating unit plants. The inducement price for the final option, substitution of R-22, cannot be assessed adequately without data on the amount of R-22 that would be required to charge new appliances and the change in operating costs for plants that manufacture R-22 units. While we suspect that the inducement price for R-22 substitution is outside the range of prices considered in this study (a conclusion supported by several simulations we performed), we cannot be sure that the other options would not be induced by prices within the relevant range.

In 1976, total manufacturing use of R-12 for home refrigerators and freezers was only 2.6 percent of total domestic sales of R-12, and only 1.4 percent of total domestic sales of non-R-22 CFCs. By 1990, the percentages will be slightly smaller. Therefore, our inability to specify the shape of the home appliance manufacturing demand schedules does not seriously constrain our ability to reach good estimates of the outcomes of a marketable permit strategy. A more serious concern about not having specified a home appliance CFC demand function is that it limits our ability to estimate the economic effects of a marketable permit strategy on this industry.

The limitation is bounded, however. If we assume that home appliance manufacturing demand is perfectly inelastic, we can be sure that our estimate of the cost imposed by marketable permits (or taxes) is an upper bound.

Suppose that a marketable permit or tax strategy raised the cost to users of R-12 as high as $2.50 per pound. The cost of producing an appliance that holds a refrigerant charge as large as 20 ounces would rise by only $2.60. Given that the appliance costs the consumer several hundred dollars, the effect on the final product price of this rise in refrigerant costs is trivial. There would probably be no effect on final product output for the home appliance market. Moreover, to the extent that firms would find it cost-effective to reduce their usage of R-12, the increase in appliance production costs would be smaller than the foregoing estimate.

It is true that some firms would find that their production costs would rise more than others. Plants that produce rotary compressors and those that have smaller market shares would be at a disadvantage, the former because they use more R-12 per appliance and the latter because the total R-12 savings per year might not offset the capital investments that would help reduce R-12 use. We do not anticipate, however, that any plants would be put out of business. Since appliances made by different manufacturers already have different selling features, an added price differential of as much as two or three dollars per appliance would probably not have a substantial effect on the market share of different manufacturers.

With regard to servicing, we are confident that the demand for R-12 is perfectly inelastic within the price range under consideration. A change in servicing costs of as much as two or three dollars per service call would not lead customers to forgo appliance repair. The serviceman's option of recovering R-12 at service is clearly not cost-effective in the price range considered in this study.

Assuming that both the manufacturing and servicing demand schedules are perfectly inelastic, R-12 total demand for home appliances would be about 7.1 million pounds in 1980, rising at an average annual rate of 2.9 percent per year to 9.4 million pounds in 1990.

## MANDATORY CONTROL CANDIDATES

All four of the control options that appear to be feasible and effective candidates for mandatory controls apply to regulation of the manufacturers. The costs to different firms of complying with mandatory helium leak testing depend in part on the level of R-12 leak testing losses by plant. In a comparison between a rotary unit manufacturer and one who produces the same number of reciprocating units, the rotary producer might find compliance with the regulation less costly because his R-12 saving might be greater. More generally, we suspect that the compliance cost for any manufacturer would be very modest and could be passed through to final consumers through a price increase for appliances of just a few cents per unit.[9] At the same time, the emissions reduction from the policy would be tiny, adding up to little more than one million pounds between 1980 and 1990.

All of the foregoing comments apply equally to a mandatory control requiring recovery of R-12 at rework. Although IR&T's estimates of rework emissions suggest that the policy would reduce cumulative emissions by 1990 by three million to four million pounds, we suspect that estimate is somewhat high.

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[9] General Electric, the largest producer, would not incur any compliance costs at all because that company already uses helium for leak testing. In fact, GE might benefit from the new market for its helium leak testing system.

Requiring all new appliances to be made with reciprocating compressors would eventually reduce R-12 emissions by 30 to 40 percent per year, assuming rotary units comprise half the market. If the adjustment occurs through retooling of existing rotary plants, it would cost perhaps $23 million and take a few years to implement. Furthermore, since the long-run effects on servicing emissions would not be felt until the stock of rotary appliances is disposed, the effect on emissions prior to 1990 would be small. Assuming that rotary units would otherwise comprise half the market, we estimate that the cumulative emissions reduction by 1990 would be just about one million pounds.

Although the $23 million retooling costs look large, they would be partly offset by savings to the manufacturers in reduced refrigerant expenditures. Moreover, the cost effect per appliance does not appear large. After constructing several simulations of market outcomes using different assumptions about market structure, we conclude that the effect on appliance prices of this mandatory control would be less than a dollar per appliance. However, because there is a remote possibility that some rotary manufacturers might suffer serious financial losses from this policy, further analysis should be undertaken before implementing it.

Substitution of R-22 for R-12 is an even more costly control candidate but offers even larger long-term emissions improvements. The policy would be more even-handed in its effects on different manufacturers than requiring use of reciprocating compressors. However, several alternative simulations suggest it would have a greater effect on final product prices, raising them as much as $5 to $20 per appliance, depending on manufacturing operating costs and the amount of R-22 required for initial charges. Because this option would take a few years to implement and a few more years to achieve an effect on servicing emissions, the cumulative effect on R-12 emissions by 1990 would be to reduce them by only four to five million pounds. However, by the year 2005, when the appliance stock has turned over, home appliance emissions of R-12 would reach zero.

None of the preceding control candidates is included in the benchmark set of mandatory controls for comparison with economic incentive policies.

## CONCLUSIONS

Home refrigerators and freezers contribute less to CFC emissions than any of the other major product areas studied in this report. They even emit less than some of the "miscellaneous" products we have investigated. By 1990, even in the absence of policy action, home appliances will emit less than 10 million pounds of fully halogenated CFCs.

There are a few ways to reduce emissions in this product area without imposing exorbitant costs on the industry or its customers, but the emissions effects of the options are small. Alternatively, substitution of R-22 would eventually eliminate R-12 emissions from these products, but at high cost and with considerable delay. In comparison with other product areas where emissions are far greater and can be reduced more substantially and at less cost, home appliances are a poor target for regulatory action.

# III.G. RETAIL FOOD STORE REFRIGERATION SYSTEMS

## INTRODUCTION

Retail food store refrigeration systems are used to refrigerate the food and beverages in display cases, and to store meat, produce, dairy products, frozen food and ice cream in walk-in coolers. Refrigeration systems have two temperature ranges: medium temperatures for meat and dairy products, and low temperatures for frozen food and ice cream.

The refrigerant commonly employed for low temperature applications is R-502, which is an azeotrope (constant-boiling blend) consisting of 48.8 percent R-22 and 51.2 percent R-115. R-12 was used in low temperature systems until the early sixties, when the development of R-502 offered a more energy efficient alternative. While R-12 is generally chosen for medium temperature systems, the use of R-502 for this purpose in new systems has been increasing in recent years, reportedly because of the advantage of handling only one refrigerant for both temperature ranges.

R-22 was once employed in both low and medium temperature applications, but today is used only at medium temperatures. With the exception of one company, the industry recommends against using R-22 even at medium temperatures, because R-22 generates excessive heat in the compressor and tends to break down compressor oil and corrode motors. Most manufacturers now install R-22 systems only if they are specifically requested by a customer.

Current trends in refrigeration system design tend to increase average refrigerant charge per system. Because refrigeration equipment accounts for as much as half of a food store's total energy requirements, refrigeration equipment manufacturers have been marketing several energy-saving options. One such option, heat recovery, is being introduced in nearly all new stores and retrofitted into many older stores. It requires a larger refrigerant charge. The charge is also affected by the design of the automatic defrost feature of a system. Hot-gas defrost, which has become increasingly popular, requires more refrigerant. A larger refrigerant charge is also required for remote air-cooled condensers, which are displacing the traditional water-cooled condensers ostensibly because of water conservation.

The total number of retail food stores is expected to decline by about 15 percent between 1976 and 1990, but the average store size will increase and the average refrigerant charge per store will increase. Hence, the refrigerant bank in food stores will grow from about 74 million pounds in 1976 to approximately 120 million pounds in 1990.

Purchases of refrigerant to charge and service food store systems is projected to grow slowly from 23 million pounds in 1976 to 27 million pounds in 1990. The use of fully halogenated CFCs, which exclude R-22 and the half of R-502 that is R-22, is growing even more slowly. In 1976, 16 million pounds of non-R-22 refrigerants were used to charge and service food store systems. By 1990, these uses will be only about 18 million pounds.

## USE AND EMISSIONS

Industry statistics for total shipments of retail food store refrigeration systems are unavailable. Consequently, the IR&T estimates (see Neill et al., 1979) of refrigerant use, emissions, and stocks are derived from information concerning retail food stores. Since the average refrigerant requirements depend on the quantity of food needing refrigeration, store sales volume serves as a proxy for refrigerant needs. For analysis, IR&T separates sales volume into four categories:

1. Annual food sales of over $2 million.
2. Annual food sales ranging from $1 million to $2 million.
3. Annual food sales of between $500 thousand and $1 million.
4. Annual food sales under $500 thousand.

Table 3.G.1 presents the estimated numbers of retail stores in each category for 1976 and 1990. The 1990 values were projected from historical trends, incorporating provisions for new construction and permanent closings.

Table 3.G.1

NUMBER OF RETAIL FOOD STORES, 1976 AND 1990

| Store Sales Class | 1976 | 1990 |
|---|---|---|
| Over $2 million | 20,950 | 33,330 |
| $1 million to $2 million | 11,750 | 13,000 |
| $500 thousand to $1 million | 12,000 | 12,000 |
| Under $500 thousand | 139,000 | 97,000 |
| Total | 183,700 | 155,330 |

SOURCE: Neill et al. (1979), Table 1, p. 7.

The values of Table 3.G.1 show that there will be a 15 percent decline in the total number of grocery stores by 1990. This reflects an estimated 30 percent decline in the number of grocery stores with sales under $500,000, which is partially offset by a 59 percent increase in the number of large supermarkets.

While the most significant factor determining refrigerant requirements is the quantity of food needing refrigeration, other influential factors include the type of refrigeration system and the degree to which energy conservation features are adopted. From data supplied by retail food industry sources, IR&T identified an average refrigerant charge for each store size which depends in part on the type of refrigerant used, the number of refrigeration components, and whether the stores are new, remodeled, or existing. The new and remodeled stores are incorporating many energy-saving techniques which require a higher refrigerant charge. Estimated refrigerant needs are shown in Table 3.G.2.

The type of refrigerants used differs between existing and new or remodeled stores. IR&T estimates of the refrigerant mix, together with the data in Table 3.G.1, permit estimates of the stock of refrigerants (the "bank") by store size for 1976 and 1990. Estimated stocks are given in Table 3.G.3.

### Table 3.G.2

### 1976 REFRIGERANT REQUIREMENTS PER STORE

(Pounds)

| Store Type | Store Sales Class<br>Over $2 Million | $1 to $2 Million | $500,000 to $1 Million | Under $500,000 |
|---|---|---|---|---|
| Existing stores | 1,500 | 1,000 | 650 | 164 |
| New and remodeled stores | 2,500 | 1,200 | 650 | 140 |

SOURCE: Neill et al. (1979), Table 6, p. 18.

### Table 3.G.3

### REFRIGERANT BANK BY STORE CLASS AND REFRIGERANT TYPE, 1976 AND 1990

(Millions of pounds)

| Store Sales Class | R-12 | R-502 | R-22 | Total |
|---|---|---|---|---|
| 1976 | | | | |
| Over $2 million | 15.71 | 12.57 | 3.14 | 31.42 |
| $1 million to $2 million | 5.88 | 4.70 | 1.18 | 11.75 |
| $500 thousand to $1 million | 5.07 | 2.34 | .39 | 7.80 |
| Under $500 thousand | 15.96 | 5.70 | 1.14 | 22.80 |
| Total | 42.62 | 25.31 | 5.85 | 73.77 |
| 1990 | | | | |
| Over $2 million | 29.16 | 50.00 | 4.17 | 83.32 |
| $1 million to $2 million | 5.46 | 9.36 | .78 | 15.60 |
| $500 thousand to $1 million | 3.70 | 3.70 | .39 | 7.80 |
| Under $500 thousand | 6.79 | 6.79 | -- | 13.58 |
| Total | 45.12 | 69.85 | 5.34 | 120.30 |

SOURCE: Neill et al. (1979), Table 9, p. 23. Components may not sum to totals because of rounding.

Annual use includes the refrigerant used in the testing of units during manufacture, replacement of losses during installation, initial charges for new units, and replacement of the refrigerant which is lost through leakage and during service. Table 3.G.4 gives both total refrigerant and non-R-22 use for 1976 and 1990 as estimated by IR&T. The average annual rate of growth of the non-R-22 use for the period is less than one percent.

As is true for other refrigeration devices, five types of refrigerant losses can

Table 3.G.4

REFRIGERANT PURCHASES FOR USE IN RETAIL FOOD STORES, 1976 AND 1990
(Millions of pounds)

| Refrigerant | Initial Charge | All Other | Total |
|---|---|---|---|
| 1976 | | | |
| R-12 | 3.90 | 6.73 | 10.63 |
| R-502 | 7.07 | 3.43 | 10.50 |
| R-22 | .60 | .90 | 1.50 |
| Total | 11.57 | 11.06 | 22.63 |
| Total non-R-22[a] | 7.52 | 8.49 | 16.01 |
| 1990 | | | |
| R-12 | 4.87 | 5.25 | 10.12 |
| R-502 | 8.04 | 7.28 | 15.32 |
| R-22 | .68 | .65 | 1.33 |
| Total | 13.59 | 13.18 | 26.77 |
| Total non-R-22[a] | 8.99 | 8.98 | 17.96 |

SOURCE: Neill et al. (1979) do not report refrigerant use. These estimates were calculated from data on emissions and food store refrigerant charges reported by IR&T.

[a] These values include all of R-12, and 51.2 percent of R-502.

occur over the lifetime of a retail food store system: manufacturing, installation, leakage, service, and disposal losses. The nature, characteristics, and magnitude of each type of loss are discussed below.

### Manufacturing Emissions

One source of refrigerant loss during manufacture is leak testing. Both R-12 (in a mixture that is 70 percent air), and R-22 (in a mixture that is 75 percent nitrogen) are used as test gases in leak testing. One of the manufacturers of refrigeration equipment currently practices reclamation of the test gas, and another plans to install a reclamation system in the near future.

On the basis of data and information from industry sources, IR&T estimates 1976 and 1990 emissions from R-12 leak testing at 400,000 and 144,000 pounds, respectively. The decline in 1990 occurs because of presumed widespread adoption of reclamation, even in the absence of regulatory control.

### Installation Emissions

In contrast with other refrigeration systems discussed in this report, food store systems receive their initial charges during installation at the food store site rather than at the system manufacturing site. In the installation process, the system is evacuated, leak tested, and charged. R-12 and R-22 are generally used to test medium temperature systems, and R-12 and R-502 are used to test low temperature systems. Isolation valves are sometimes put in during installation, to be used if an undetected loss occurs at the time of startup. However, because of its cost, this practice may not be widespread.

The emissions estimates for installation are based on IR&T's discussions with four major equipment manufacturers and on testimony before the EPA hearings.[1] The IR&T estimates of installation emissions, which vary depending on the size of the store, yield an overall average of five percent of the total recommended charge. In 1976, non-R-22 emissions of this type amounted to 468,000 pounds. By 1990, they are expected to increase to 532,000 pounds due to projected increases in installations.

### Leakage and Service Emissions

Industry sources indicate that leakage accounts for 80 percent of combined leakage and service losses. Refrigerant leakage eventually leads to a service call, and the measure of leakage and service losses includes replacement of the loss and releases by the technician during servicing procedures.

IR&T assumes that data on leakage and servicing emissions provided by one major grocery store chain were representative of the industry as a whole. In 1976, IR&T estimated these combined emissions at 10, 15, 15 and 17 percent of stocks for each store type in descending order of sales volume. On this basis, non-R-22 leakage and servicing emissions amount to about six million and 1.5 million pounds, respectively. By 1990, these emissions are expected to be 10, 10, 15, and 10 percent of refrigerant stocks, again in descending order of sales volume, leading to 6.6 million and 1.7 million pounds of non-R-22 emissions from leakage and service, respectively. The decline in the 1990 percentages for two of the store categories is due to the presumed gradual replacement of older stores having relatively high leakage and service emissions by supermarkets using more modern installations.

### Disposal Emissions

IR&T estimates disposal emissions by assuming them to be a function of store changes that cause equipment to be discarded. These changes include store closings, shiftings among store size categories, and remodelings. According to IR&T, one industry source suggests that about 50 percent of the refrigerant in a given unit can be saved by pumping it into the receiving tank before replacement with new equipment. However, this practice is currently followed only when the equipment is to be sold secondhand.

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[1] Swope (1977a).

IR&T assumes that in the two largest store categories, 85 percent of the closings, shiftouts, and remodelings would result in disposal emissions; in the two small categories, the figure is 100 percent. Non-R-22 losses of this type amount to 4.6 million pounds in 1976 and 6.9 million pounds in 1990.

### Total Emissions

The total emissions in 1976 and 1990 for each refrigerant are presented in Table 3.G.5.[2] The values illustrate that although total emissions of all refrigerants in 1990 will increase by 34 percent over 1976 levels, total non-R-22 emissions will increase by only 21 percent. This is primarily a result of the movement away from R-12 toward R-502 mentioned earlier.

The largest sources of emissions in both 1976 and 1990 are leakage and disposal. By 1990, leakage will account for 42 percent of total non-R-22 emissions. Disposal emissions for that year represent 43 percent of total non-R-22 emissions.

## INDUSTRY AND MARKET CHARACTERISTICS

The industry which produces the refrigeration equipment for the retail food stores is dominated by five firms:

Hussman Refrigerator Company, Division of Pet, Incorporated, St. Louis, Missouri.
Hill Refrigeration Company, Division of Emhard Corporation, Trenton, New Jersey.
Tyler Refrigeration Corporation, a privately held company, Niles, Michigan.
Friedrick Air Conditioning and Refrigeration Company, Division of Weil-McLain, Inc., San Antonio, Texas.
Warren-Sherer Company, Division of Kysor Industrial Corporation, Marshall, Michigan.

The first three companies account for approximately 80 percent of the market, and the last two share about 15 percent. The remaining five percent of the market is held by several small companies. The number of persons employed by Hussman Refrigerator Company is not available. The other four firms together employ about 4,000 workers. Each of these companies may produce other products, and the proportion of employment attributable to retail food store refrigeration systems cannot be determined from the available data.

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[2] IR&T made a number of assumptions in developing the emissions estimates for retail food stores. Sensitivity analyses were performed to quantify the significance of some of the central assumptions. The largest effect on emissions results from a 33 percent variability in the estimate of refrigerant stocks. This could cause total 1976 and 1990 emissions to increase or decrease by 5.7 million and 7.7 million pounds, respectively. A 50 percent change in leakage and service emissions for all stores and for stores in the two smaller categories results in a change in 1976 total emissions of about five million and 2.5 million pounds respectively; for 1990, the values are approximately 6.1 million and 1.3 million pounds. A 25 percent shift in the number of disposals could vary total 1976 emissions by 1.6 million pounds and 1990 emissions by 2.6 million pounds. A decrease of three million pounds in total 1990 emissions would result if there were a change in 1990 store composition, 25 percent fewer large stores, and 25 percent more smaller stores.

## Table 3.G.5

### EMISSIONS FROM RETAIL FOOD STORE REFRIGERATION, 1976 AND 1990

(Millions of pounds)

| Stage | R-12 | R-502 | R-22 | Total | Total[a] Non-R-22 |
|---|---|---|---|---|---|
| | | | 1976 | | |
| Manufacturing | .40 | -- | .10 | .50 | .40 |
| Installation | .39 | .15 | .06 | .60 | .47 |
| Leakage | 4.75 | 2.63 | .59 | 7.97 | 6.09 |
| Service | 1.19 | .66 | .15 | 1.99 | 1.52 |
| Disposal | 3.28 | 2.67 | .48 | 6.43 | 4.65 |
| Total | 10.00 | 6.10 | 1.38 | 17.48 | 13.13 |
| | | | 1990 | | |
| Manufacturing | .14 | -- | .04 | .18 | .14 |
| Installation | .45 | .17 | .06 | .68 | .53 |
| Leakage | 3.73 | 5.69 | .44 | 9.86 | 6.64 |
| Service | .93 | 1.42 | .11 | 2.46 | 1.66 |
| Disposal | 3.81 | 5.94 | .46 | 10.22 | 6.85 |
| Total | 9.07 | 13.22 | 1.11 | 23.40 | 15.84 |

SOURCE: Neill et al. (1979), Table 14, p. 37, and Table 15, p. 38. Components may not sum to totals because of rounding.

[a] These values include all of R-12 and 51.2 percent of R-502.

The major manufacturers of commercial refrigeration systems act primarily as the designers and assemblers of systems and depend heavily on other manufacturers to supply components including motors, compressors, condensers, receiving tanks, tubing, valves, electrical components, and other small hardware.

Future demand for refrigerant and refrigeration devices in retail food stores is dependent on the outlook for retail food sales. Much of a store's profit is derived from convenience foods requiring refrigeration. Until recently, a slowing in growth of consumer demand has restricted the growth of the industry. In constant dollars, domestic per capita food consumption for calendar year 1976 was up 2.5 percent over 1975, reflecting a slightly stronger consumer demand.

Refrigeration system costs can vary widely depending on the capacity, design, and energy efficiency of the unit. It is not likely that the cost of the refrigerant is a significant part of the total costs. In stores ranging in size from 2,500 to 35,000 square feet, the refrigerant requirements may be as high as 2,000 pounds, with refrigerant costs of about $1,700 for the initial charge. It is very likely that the average annual cost of refrigerant to the user is dwarfed both by the refrigeration system costs and also by the expenditures for energy to operate the unit.

## OPTIONS TO REDUCE EMISSIONS

IR&T identifies seven potential methods for reducing emissions from retail food store refrigeration systems. To these, we add an eighth: refrigerant recovery at servicing. For reasons explained below, only two of the options appear feasible and effective as candidates for mandatory control, and only one is included in the benchmark set of controls.

### R-22 Leak Testing at Manufacture

Since there is no technical disadvantage in leak testing with a refrigerant other than the one ultimately used in the system, any refrigerant can be used for this purpose. R-502 is not currently used, primarily because its price is about three times that of R-12. Approximately 80 percent of the refrigerant used in leak testing is R-12 and the balance is R-22.

Substitution of one refrigerant for another in this use could be induced by policies that manipulate their relative prices. Mandatory controls might be enforceable, given the small number of manufacturers to be monitored.

### R-22 Leak Testing at Installation

As in leak testing during manufacture, there is no inherent disadvantage in using R-22 for testing during installation, even if the system will ultimately contain R-12 or R-502. Since the system is evacuated prior to charging, all of the R-22 would be purged. R-12 is the refrigerant most widely used for installation leak testing because of its low cost. However, R-502 is also used to some extent, despite its much higher price.[3] Industry sources report that this occurs when R-502 will be the initial charge because installers can then use the same gas for both leak testing and charging the units.

If the price of R-12 were to rise, at some point it would become cost-effective to employ R-22 as the test gas. However, it is not necessarily true that an R-12 price higher than that of R-22 would be necessary or sufficient to induce this substitution if, as industry sources argue, the convenience to the serviceman of carrying only one or two refrigerants plays a role in his choice among test gases. Thus, if R-22 became the most common refrigerant for initial charges, it might also be used as the test gas even if it remains slightly more costly than R-12. Alternatively, if R-502 became the most common refrigerant for initial charges, it might become the most commonly used test gas even though it is more costly than both R-12 and R-22. As detailed below, our analysis presumes that only a portion of test gas use is sensitive to relative prices of different refrigerants, and that a portion is sensitive to the choice of refrigerant for initial charges.

Enforcement of a mandatory requirement to use R-22 as the test gas would be virtually impossible at the thousands of installation sites where testing occurs each year. Therefore, this candidate for mandatory controls is likely to be very ineffective and is not considered further in this study.

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[3] In 1976, the estimated price per pound of R-502 was $1.11, while the price of R-12 was 41 cents.

### R-502 Use in Medium Temperature Systems

R-502 is presently used in almost all low temperature applications (freezing), while most medium temperature applications (cooling) use R-12 or R-502. The same compressor can be used for low temperature systems employing R-502 and medium temperature systems employing R-12. For R-502 to be used in medium temperature applications, a different compressor is necessary. Since a small amount of R-502 is already used in medium temperature systems, the compressors are presumably available from the component manufacturers.

The disadvantage of this option is that R-502 is more expensive than R-12 and R-22 and, at present prices, would not be cost-effective. However, if the price of R-12 were to rise above that of R-502, there would be an incentive to use the latter refrigerant, at least in all new medium temperature systems. Alternatively, it would also be possible to enforce this option as a mandatory control because there are only a few manufacturers to monitor.

Universal adoption of this option would reduce R-12 emissions from leakage and servicing. Disposal emissions would also be reduced, but with a time delay.

### R-22 Use in All Applications

Although R-22 has been used in low temperature applications in the past, it is not presently used for this purpose because its high pressure requires dual compressors. As mentioned earlier, even at medium temperature, it is disadvantageous to employ the refrigerant because some compressor manufacturers will not guarantee their equipment for use with R-22. Because the technical problems of R-22 performance make it unattractive as a substitute for R-12 and R-502, we presume R-22 substitution could not be induced by R-12 prices in the range considered in this study. As a mandatory control, R-22 substitution is not included in the set of benchmark candidates because it is an alternative to R-502 substitution in medium systems and because implementing R-22 substitution would take time, implying that much of its emissions effects would not be observable until after 1990.[4]

### Recovery and Reclamation at Disposal

Retail food store refrigeration systems are replaced either because they no longer satisfy a store's requirements and are sold second-hand, or because they no longer function properly. In the former case, the refrigerant charge is often pumped into a receiver tank for later use in the new system, and the old system is sold on the second-hand market. However, IR&T reports that when the systems are disposed, even though they are still functional, the refrigerant is purged to the atmosphere. In at least some of these cases, the refrigerant probably could be recovered and reused.

From calculations not reported in the IR&T document, an IR&T researcher concludes that recovery at disposal ought to be cost-effective at current CFC prices, especially for R-502. The calculations assumed that the labor charge for the procedure would be just $15 and that there are no lost sales during the procedure. However, even if we assume that the labor costs plus forgone sales would be $200 or $300 we cannot explain why stores would not be undertaking this activity, at least for R-502. Because we have no explanation for the failure of stores to undertake what appears to be a money-saving operation, we are reluctant to include this option in our analysis. It may be, for example, that there are technical problems in reclaiming R-502, or that costs are much higher than we might guess, or that there is less charge left in a disposed unit than IR&T estimates. In any case, further technical assessment of this option is warranted because it holds the potential for substantially reducing emissions, which amount to a few million pounds each year.

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[4] As explained below, we do not consider the option of requiring existing systems to be replaced.

### Better Installation Procedures

Proper system installation generally requires two or three days of a contractor's time. It is frequently the last thing done before a retail food store opening. Since it is costly to delay the store opening for even one day, installation is often performed quickly. Connections may be improperly fitted, causing higher leakage rates, and access to allow proper servicing later may not be developed adequately.

Better installation could reduce leakage and service emissions over the lifetime of the system. Reducing the required number of service calls each year would save the store labor costs. For large supermarkets, at least, the savings could be significant enough to make this option attractive at higher refrigerant prices, as explained below. However, this option is a poor candidate for control because of the difficulties of enforcement.

### Preventive Maintenance Programs

Institution of preventive maintenance on a monthly or quarterly basis could reduce leakage and service emissions. IR&T estimates that a quarterly program of this type would cost the store about $400 per year for labor. The potential benefits to the store of such a program would be a reduction in the requisite number of annual service calls by 1.5 visits (saving the store about $150 per year) and a reduction in annual leakage and servicing losses of about 15 percent. Even a large supermarket would thus save only about 40 pounds of refrigerant annually, at a net cost for added labor charges of $250 per year. For supermarkets, such a program would be cost-saving on balance only if refrigerant costs rose to $6.25 or more per pound.

Preventive maintenance could not be induced by refrigerant prices within the range considered in this study. Moreover, since such programs are clearly not cost-saving at current refrigerant prices, there are strong incentives for stores to evade compliance with mandatory controls. This option is not considered here as a candidate for mandatory controls.

### Recovery at Servicing

Although this option is not mentioned by IR&T, it seems reasonable to suppose that if refrigerant is recoverable at disposal, it would also be recoverable at servicing. This option, like that for disposal recovery, would be available without added capital investment to stores in the two largest sales categories because they typically have receiver tanks. For those stores, the cost of pursuing the option consists of forgone food sales due to the longer shut-down of refrigeration equipment during service plus whatever extra labor costs are involved. We do not have data on these costs, but the absence of recovery at servicing may suggest that the costs of the procedure outweigh the value of the refrigerant that would be recovered, at least at current refrigerant prices.

This option is not treated here as being responsive to increased refrigerant prices within the price range under consideration, nor is it a candidate for mandatory control. It seems unlikely that refrigerant savings, even at higher prices, could outweigh the costs of the procedure because the potential refrigerant recovery is very small. For example, a new or remodeled store in the largest size category—the kind of store with the highest annual servicing losses—loses on average only about 88 pounds of R-12, 150 pounds of R-502, and about 12 pounds of R-22 during servicing each year. Only one of these refrigerants could be recovered at any one time. Even if the costs of the procedure were as little as $250, it would not be cost-saving even at the highest refrigerant prices considered in this study.[5] It is even less likely that the procedure is cost-saving at current refrigerant prices, so under a mandatory control strategy there would be a strong incentive for stores to attempt to evade the control, making enforcement difficult.

## CFC DEMAND SCHEDULES

Because refrigerant appears to be a very small component of refrigeration system costs, we do not expect the amount of refrigeration in retail food stores to be noticeably affected by changes in refrigerant prices within the range considered here. It is true that changing the refrigerant price will have differential effects on the refrigeration costs of different stores; larger stores will experience a larger total cost increase, but with unknown (but almost certainly very small) differences in effects on the cost of refrigeration per unit sales of refrigerated foods. If all types of stores were in competition in precisely the same markets, the differential cost effects of a change in refrigerant prices could, in principle, affect the competitive standing of stores of different types or sizes. However, stores operate in different geographical markets and, even in the same locality, serve different consumer needs (e.g., weekly marketing vs. quick-stop, convenience shopping). Although a few stores here and there throughout the country might be affected adversely by increased refrigerant prices, it is unlikely that many stores will experience a noticeable effect on sales from the passing on to food customers of the rather minor cost effects postulated here.[6]

The following analysis presumes that refrigerant prices in the range considered here would not induce replacement of existing systems. It is possible that some stores might be induced to advance their plans for remodeling if refrigerant prices rose, just as rising energy costs have induced some remodeling efforts to begin sooner than they otherwise would. However, we do not expect this effect to be large enough to be readily observable or to have much effect on emissions.

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[5] At a maximum price for R-12 or CFC-115 of $2.50 per pound, complete recovery and reuse of R-12 would save only $220, while complete recovery and reuse of R-502 would save only $240.

[6] IR&T estimates that the number of "Mom and Pop" stores is declining at seven to nine percent per year. These same stores also are likely to feel the pinch of higher refrigerant prices more than their larger competitors. As a practical matter, it would be virtually impossible after the fact to tell whether higher refrigerant prices contributed to the shutdown of one of these small stores.

We discuss three sources of demand. The first, manufacturing demand, describes the price responsiveness of refrigerant purchases for leak testing by the system manufacturers. The second, installation demand, covers purchases of refrigerant for leak testing during installation and for charging the installed system. The third demand profile describes servicing use, which is determined by the characteristics of the entire stock of refrigeration equipment. Because the amount and type of refrigerant used for installation and servicing of systems in retail stores varies according to the store size, we develop the installation and servicing demand profiles for each of the four store sizes separately.

For each source of demand, there are up to three different CFC demand schedules, for R-12, R-22, and R-502. We assume that policy action would not be taken to modify the price of R-22, and that its price (in 1976 dollars) will remain constant at 64 cents per pound throughout the period 1980 to 1990. The current R-502 price of $1.11 is treated as a simple weighted sum of the prices for R-22 and CFC-115, implying that the price of CFC-115 in 1976 was about $1.56 per pound. Policy action to raise the price of CFC-115 would raise the price of R-502, but only by about one-half cent for each one cent increase in the CFC-115 price because the cost of the half of R-502 that is R-22 would be unchanged. The 1976 bulk price of R-12 was 41 cents per pound.

Section IV explains that an economic incentives policy should strive to equalize the price penalty (i.e., the tax or marketable permit price) per unit of ozone depletion among different CFCs. Using chlorine content as a simple proxy for ozone depletion potential, CFC-115 is one-half as hazardous as R-12. Hence, for each one cent increase in the penalty for R-12, the penalty for CFC-115 should rise one-half cent, and the price of R-502 would rise one-fourth cent. This pricing relationship is reflected in the demand schedules developed here.

### Manufacturing Demand

Given the average annual rates of growth implied by Table 3.G.5, 327,000 pounds of R-12 would be purchased by system manufacturers for leak testing in 1980. A smaller amount of R-22, 82,000 pounds, would also be used for this purpose.

If the price of R-12 rose to 65 cents per pound, slightly above the R-22 price, the manufacturers would find it cost-effective to use R-22 exclusively for leak testing. There is no apparent disadvantage in the substitution, since some R-22 is already employed for this purpose. The reduction in R-12 purchases that could be achieved by implementation of this option is 327,000 pounds in 1980; in 1990, the value would be 144,000 pounds. A corresponding increase for R-22 use would result.

### Installation Demand

The same compressor can be used for R-12 in a medium temperature system and R-502 in a low temperature system, but a different compressor is required in a system which employs R-502 at medium temperature. Information on the relative costs of producing or operating the two compressors is unavailable. However, the trend toward using R-502 in medium temperature systems suggests that any cost differential partially offsets the higher cost of R-502 for charging the system, at least for most customers. The demand estimates arbitrarily assume that if the price difference decreased by 20 percent, all new medium temperature systems would be charged with R-502. The policy prescription to achieve this outcome is to raise the price of R-502 one-fourth as much as the price increase in R-12 until the difference between the two prices declines by 20 percent. This procedure leads to prices of 60 cents and $1.16 for R-12 and R-502, respectively.[7]

Because of the convenience of using a single refrigerant for installation leak testing as well as charging, implementation of this option would probably eliminate some or all use of R-12 for testing during installation. A conservative estimate is that half of all R-12 leak testing would be replaced by the use of R-502. If the price of R-12 rose just a little higher, to 65 cents per pound, the remainder of the R-12 leak testing use would be supplanted by R-22 use. The corresponding R-502 price at which this would occur is $1.17. Finally, we assume that all leak testing would be done using R-22 if the R-502 price reached $1.30, corresponding to an R-12 price of $1.17.

Installation use of R-12 and R-502 could be further reduced if all new medium temperature systems were charged with R-22.[8] For the manufacturers, it is estimated that retooling, research, and startup costs for this adjustment would be about $24 million, leading to higher system costs. Even leaving the increase in system costs aside, however, we find that the retail food stores would not be induced to purchase such systems by refrigerant prices in the range considered here. It is estimated that the switch to R-22 would lead to increased servicing of the systems, at a cost to the average retail store of $400 per year. A large store would reduce the combined use of R-12 and R-502 by about 150 pounds. To make this cost effective, the prices of R-12 and R-502 would have to rise by more than $3 per pound. Smaller stores would require even greater increases in non-R-22 prices to induce the use of R-22 because the added servicing costs for the R-22 systems would be similar to those for large stores, but the potential reduction in R-12 and R-502 use would be less.

## Servicing Demand

The servicing demand for each refrigerant depends on the refrigerant usage of the entire stock of equipment. This would be affected by any tendency for new systems to use R-502 or R-22 rather than R-12, but only after a significant portion of the equipment stock was composed of the newer systems.

Aside from this indirect effect on servicing demand, which is included in the demand schedules reported below, the only potential effect of refrigerant prices on servicing demand would be to induce better installation, preventive maintenance programs, or recovery of servicing losses. Earlier, we noted that the last two of these options would probably not be undertaken at refrigerant prices in the range considered here. Consider, for example, a very large store, with annual leakage and servicing losses of 88 pounds (for all refrigerants used in the store) and typical daily profits of $1,000. To delay opening an extra day to allow better installation would cost the store not only the loss of a day's profits, but also about $500 in extra installation charges. Amortized over five years at 20 percent, the annualized cost would be $302. In exchange, the store might save about two service calls per year, at $100 each, plus the value of the refrigerant losses prevented. The better installation would pay for itself only if refrigerant prices were at least $3.45 per pound—outside the range for this study. A similar result would apply to smaller stores because although their daily profits are lower, so are their annual leakage and servicing losses.

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[7] Requiring a 50 percent reduction in the differential leads to price outcomes of $0.88 and $1.23 for R-12 and R-502, respectively.

[8] IR&T indicates that a significant amount of research and development, including system redesign, would be required before R-22 could be used in low temperature applications. We presume that this option would not be motivated by prices in the range considered in this study.

In summary, servicing demand is affected only by the choice among refrigerants in new systems, and then only with a lag as the existing equipment stock is replaced.

### Demand Summary

Table 3.G.6 summarizes the demand results described above for R-12. Table 3.G.7 summarizes the corresponding use results for R-502. As for R-22, at current prices its use in 1980 would be 1.44 million pounds and its use in 1990 would be 1.32 million pounds. If the price of R-12 rose to 65 cents, the 1980 use of R-22 would increase by 0.53 million pounds, and its 1990 use would increase by 0.34 million pounds. If the price of R-502 rose to $1.30, the use of R-22 would rise another 0.35 million pounds in 1980 and another 0.77 million pounds in 1990.

Table 3.G.8 reports the emissions effects of alternative prices for R-12 (and corresponding prices for R-502) achieved in 1980 and maintained at that level through 1990. The emissions of R-502 rise initially as the prices of R-12 and R-502 rise, because R-502 replaces R-12 as the charge in all new medium temperature systems.

## MANDATORY CONTROL CANDIDATES

One candidate suitable for inclusion in the set of benchmark mandatory controls is conversion to R-22 for leak testing at manufacture (but not at installation). At 1976 refrigerant prices, this control would increase manufacturers' costs by 24 cents per pound of test gas. Assuming that the use levels (in pounds) of the alternative test gases would be equal, the reduction in 1980 use of R-12 of 0.33 million pounds would impose compliance costs of $79,000, and the reduction in 1990 use of 0.14 million pounds would impose compliance costs of $34,000 (in constant 1976 dollars). The cumulative reduction in R-12 emissions under this mandatory control would be 2.5 million pounds between 1980 and 1990. The cumulative compliance cost, discounted at 11 percent per year, would be $587,000.

There are also three types of mandatory controls that involve specifying the

## Table 3.G.6

### R-12 DEMAND SCHEDULE FOR RETAIL FOOD REFRIGERATION, 1980 AND 1990[a]

(Millions of pounds of R-12 used)

| Bulk Price of R-12 (1976 $) | Option Induced | Manufacturing | Installation[b] | | | | Servicing[b] | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | A | B | C | D | A | B | C | D | |
| | | | | | 1980 | | | | | | |
| 0.41 | None | .33 | 3.56 | .85 | .41 | .04 | 1.96 | .78 | .70 | 2.14 | 10.77 |
| .60 | R-502 in medium temperature systems | .33 | 0.15 | .04 | .01 | -- | 1.63 | .67 | .64 | 2.13 | 5.60 |
| .65 | R-22 leak testing | -- | -- | -- | -- | -- | 1.63 | .67 | .64 | 2.13 | 5.07 |
| | | | | | 1990 | | | | | | |
| 0.41 | None | .14 | 3.98 | .87 | .41 | .04 | 2.92 | .51 | .56 | .68 | 10.11 |
| .60 | R-502 in medium temperature systems | .14 | .17 | .04 | .01 | -- | .63 | .11 | .12 | .15 | 1.37 |
| .65 | R-22 leak testing | -- | -- | -- | -- | -- | .63 | .11 | .12 | .15 | 1.01 |

NOTE: Dashes indicate zeros.

[a] Calculations explained in text.

[b] A is stores with over $2 million annual sales; B is stores with annual sales of $1 to $2 million; C is stores with annual sales of $500,000 to $1 million; D is stores with annual sales under $500,000.

type of refrigerant to be used: R-502 or R-22 might be required in medium temperature systems, and R-22 might be required in low temperature systems. In principle, any of these controls might be implemented not only for new systems but also for replacement of existing systems that do not conform to the controls. Since IR&T does not report estimates of the costs of various systems, we cannot assess the cost of compliance with regulations requiring replacement of systems. We can speculate, however, that some small stores would need assistance to meet the need for short-term capital to comply with the controls, and some might even be driven out of business. Moreover, the emissions benefits of such a strategy are likely to be minor. First, older R-12 units are due for replacement in the next few years in any case, and regulations prohibiting their resale together with controls on new equipment would be nearly as effective as replacement regulations in reducing emissions. Second, the total non-R-22 emissions from this product area is not very large compared with that of other product areas.

Use of R-502 exclusively in all new medium temperature systems cannot be costed precisely because we lack information on the costs of R-502 and R-12 sys-

## Table 3.G.7

### R-502 USE SCHEDULE FOR RETAIL FOOD REFRIGERATION, 1980 AND 1990[a]

(Millions of pounds of R-502 used)

| Bulk Price of R-502 (1976 $)[b] | Option Induced | Manufacturing | Installation[c] | | | | Servicing[c] | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | A | B | C | D | A | B | C | D | |
| | | | | | 1980 | | | | | | |
| 1.11 | -- | -- | 5.70 | 1.36 | .40 | .04 | 2.33 | .75 | .41 | .89 | 11.89 |
| 1.16 | R-502 in medium temperature systems[d] | -- | 9.12 | 2.18 | .80 | .07 | 2.65 | .86 | .47 | .89 | 17.04 |
| 1.30 | R-22 leak testing | -- | 8.85 | 2.12 | .78 | .07 | 2.65 | .86 | .47 | .89 | 16.69 |
| | | | | | 1990 | | | | | | |
| 1.11 | -- | -- | 6.38 | 1.40 | .40 | .04 | 5.00 | .88 | .56 | .68 | 15.34 |
| 1.17 | R-502 in medium temperature systems | -- | 10.19 | 2.23 | .80 | .07 | 7.29 | 1.28 | .99 | 1.21 | 24.09 |
| 1.30 | R-22 leak testing | -- | 9.90 | 2.17 | .78 | .07 | 7.29 | 1.28 | .99 | 1.21 | 23.69 |

NOTE: The schedule is not, strictly speaking, a demand schedule because the price of a substitute, R-12, is not held constant.

[a] Calculations explained in text.

[b] Analysis assumes that an R-502 price of $1.11 corresponds to an R-12 price of 41 cents; that $1.16 corresponds to an R-12 price of 60 cents; that $1.30 corresponds to an R-12 price of $1.17.

[c] A is stores with over $2 million annual sales; B is stores with annual sales of $1 to $2 million; C is stores with annual sales of $500,000 to $1 million; D is stores with annual sales under $500,000.

[d] Results include effect of conversion to R-502 for some installation leak testing at $1.17.

tems. However, by making use of the assumptions described above for the CFC demand analysis, we can obtain an estimate of compliance cost that is comparable to the estimate of the economic incentive necessary to induce R-502 use. Consequently, we can include this option in the benchmark set of mandatory controls. Since the demand analysis presumes that R-502 use would be induced if the price differential between R-502 and R-12 declines by 14 cents (1976 dollars), the compliance cost for reducing R-12 use for initial charges at installation and for servicing would be 14 cents per pound of R-12 reduction. We assume also that half of R-12 use for installation leak testing would be converted to R-502 if this control were implemented. At current refrigerant prices, that R-502 is sometimes used despite its higher price implies that the convenience value of using a single refrigerant for leak testing and initial charge would be about 70 cents per pound. This value is used in the calculation of compliance costs for the R-502 conversion in installation leak testing.[9]

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[9] That is, we presume that installers would charge the retail food store the same installation fee to use R-502 as the test gas or to use R-12 with an inconvenience valued at 70 cents per pound. As the

## Table 3.G.8

### REFRIGERANT EMISSIONS EFFECTS OF PRICE RESPONSES BY RETAIL FOOD STORES, 1980 AND 1990

| Bulk Price of R-12 (1976 $) | Corresponding Bulk Price of R-502 (1976 $) | Emissions Effect (millions of lb) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1980 | | 1990 | | 1980-1990 Cumulative | |
| | | R-12 | R-502 | R-12 | R-502 | R-12 | R-502 |
| .41 | 1.11 | -- | -- | -- | -- | -- | -- |
| .60 | 1.16 | -.071 | +.71 | -3.88 | +3.88 | -20.4 | +20.4 |
| .65 | 1.17 | -1.24 | +.71 | -4.22 | +3.88 | -22.7 | +20.4 |
| 1.17 | 1.30 | -1.24 | +.36 | -4.22 | +3.11 | -22.7 | +14.6 |

SOURCE: Calculations from data in Tables 3.G.4 and 3.G.7. Cumulative effect estimates assume constant average annual rate of change between 1980 and 1990, by emissions source. Effects for 1980 and 1990 use results of effects on R-12 and R-502 demand, adjusted for changes in amounts used for initial charges.

NOTE: Entries indicate total emissions effect assuming indicated refrigerant prices are attained in 1980 and maintained at that level throughout the period to 1990.

Since conversion to R-502 in medium temperature systems and use of R-22 test gas at manufacturing are the only two control candidates included in the benchmark, Table 3.G.9 shows the control analysis results for both options, thereby summarizing the overall benchmark control estimates for this product area.

As an alternative to mandated R-502 use, the use of R-22 in all new medium temperature systems could be mandated. IR&T does not estimate the cost to industry of complying with this regulation, nor the time lag (if any) required for implementation. If the mandate could be implemented immediately, the cumulative reduction in R-12 emissions would be the same as that estimated above, 12.2 million pounds by 1990. In addition, there would be some reduction in R-502 emissions relative to the baseline case, but this cannot be estimated from the IR&T data because they do not provide separate estimates of R-502 use in medium and low temperature systems.

Somewhat more information is available on the implications of mandating R-22 use in all new systems, for low as well as medium temperatures. According to IR&T, the cost of compliance to the industry as a whole would be about $24 million. There would also be added costs to the industry (which would be passed on to food consumers) due to the increased costs of the systems, their original charge, and their servicing. There is no information about the time required for implementation, but the stated need for retooling and redesign suggests that several years might be required. If the mandate could not be implemented until, say, 1985, the

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amount of leak testing for R-502 systems increases, the stores (in aggregate) either pay more total inconvenience costs or more for the R-502 to test the systems. The analysis assumes the stores pay for more use of R-502.

### Table 3.G.9

### BENCHMARK MANDATORY CONTROL ANALYSIS RESULTS FOR THE RETAIL FOOD PRODUCT AREA, 1980 AND 1990[a]

| | 1980 | 1990 | Cumulative 1980-1990 |
|---|---|---|---|
| Control Candidate: R-502 Use in New Medium Temperature Systems | | | |
| Reduction in R-12 emissions:[b] millions of pounds | | | |
| Installation leak testing | 0.20 | 0.22 | 2.3 |
| Servicing | 0.51 | 3.66 | 18.1 |
| Total | 0.71 | 3.88 | 20.4 |
| Compliance cost: millions of 1976 dollars | | | |
| Initial charge | 0.62 | 0.68 | 4.4[c] |
| Installation leak testing | 0.14 | 0.15 | 1.0[c] |
| Servicing | 0.07 | 0.51 | 1.2[c] |
| Total | 0.83 | 1.34 | 6.7[c] |
| Control Candidate: R-22 Use for Leak Testing at Manufacture | | | |
| Reduction in R-12 emissions:[d] millions of pounds | | | |
| Total | 0.33 | 0.14 | 2.5 |
| Compliance cost: millions of 1976 dollars | | | |
| Total | 0.08 | 0.03 | 0.6[c] |
| Combination of Benchmark Controls | | | |
| Reduction in R-12 emissions | 1.04 | 4.02 | 22.9 |
| Compliance cost | 0.91 | 1.37 | 7.3[c] |

[a] Calculations explained in text.

[b] Emissions of R-502 would increase commensurately. Note that the reduction in R-12 use for initial charges imposes compliance costs but does not directly reduce emissions. The 1980 reduction in R-12 use for initial charges would be 4.46 million pounds, which would be replaced by increased use of R-502. The 1990 reduction in R-12 initial charges would be 4.86 million pounds.

[c] Cumulative compliance cost estimates assume a discount rate of 11 percent.

[d] Emissions of R-22 would increase commensurately.

full emissions effect of this option would not be felt until about the year 2000, when the existing equipment stock will have been disposed. By 1990, the cumulative reduction in R-12 emissions would be about 33 million pounds, and the cumulative reduction in R-502 emissions would be about 39 million pounds (less than 10 million pounds in R-12 equivalent units). Although this option would eventually eliminate all non-R-22 emissions from this product area, the small share of the effect that would occur before 1990 together with the uncertainties about the compliance costs make this option a poor candidate for inclusion in the benchmark controls.

A further consideration in evaluating the desirability of mandated substitution of R-22 is its potential effect on energy utilization. Although no precise data on the energy implications of this option have yet been cited, industry sources uniformly agree that a substantial energy penalty would be incurred. This option clearly deserves further technical assessment to determine its costs, both in terms of its impact on consumers and manufacturers and in terms of its energy implications.

## CONCLUSIONS

In 1976, retail food store refrigeration systems were responsible for well under five percent of total emissions of CFCs other than R-22. By 1990, non-R-22 emissions from this product area will account for less than two percent of the total. Some reductions in these emissions would probably be induced by rather modest changes in the prices of R-12 and R-502, and some could be achieved through mandatory controls without imposing exorbitant compliance costs on the industry or on food consumers.

To achieve larger emissions gains, it would be necessary to convert to R-22 or some other refrigerant, a change which appears feasible but much more costly than the other emissions-reducing options. This is a long-term strategy, yielding much of its emissions effects after 1990. Whether such a strategy should be pursued would depend on results from further technical and economic assessment of R-22 conversion.

# III.H. MISCELLANEOUS APPLICATIONS

## INTRODUCTION

In 1976, about five percent of total nonaerosol CFC sales were used for the products discussed in this section. Two of these "miscellaneous" products, sterilants and liquid fast-freezing systems, are relatively important because their CFC use is already comparable to the smaller refrigeration product uses and is growing. The remaining miscellaneous products are extremely small users of CFCs but are of interest to the various federal agencies that are participating in the CFC policy-making process.

## USE AND EMISSIONS

### Sterilants

Although steam is the traditional sterilant for use in hospitals and institutions, a large and growing list of devices and patient care products cannot withstand exposure to steam and must be sterilized with gas. In addition, the use of gas sterilants has increased in recent years because hospitals increasingly favor the use of disposable instruments that have been presterilized by industrial suppliers.

CFCs are used to dilute ethylene oxide in medical-instrument sterilants, the most common being "12/88," a gaseous mixture of 88 percent CFC-12 and 12 percent ethylene oxide by weight.

There are alternatives to 12/88 gas for this application, such as pure ethylene oxide and blends of ethylene oxide and carbon dioxide. However, pure ethylene oxide is highly flammable and toxic in high concentrations; and the carbon dioxide blends, while less flammable and less toxic than pure ethylene oxide, are less efficient sterilants than 12/88 and must be kept in higher-pressure cylinders that are more difficult to handle safely.

Sterilization is performed in specially constructed chambers in which temperature, humidity, and length of exposure to the sterilant gas can be controlled, sometimes for several hours. Whether sterilization is performed in the hospital or by producers of disposable instruments, the sterilizing gas is discarded either by venting it to the atmosphere or by adding water and flushing it down a drain. In both cases, emissions are prompt.

DuPont has estimated that during 1976, between 11 and 13 million pounds of CFC-12 were blended with ethylene oxide for sale as a sterilizing gas.[1] DuPont also estimates that industrial sterilant applications account for 55 percent of the 12/88 sales, and that hospitals and institutions account for 45 percent. But Union Carbide, one of the firms that blends the mixture, states that the proportions are 75 percent industrial and 25 percent hospital/institutional.[2] While a contact at Pennsylvania Engineering Company confirms the DuPont estimate, the Health Industry Manufacturers' Association (HIMA) suggests that the proportions are 80 percent industrial and 20 percent hospital/institutional.[3] Presuming that DuPont would have more knowledge of production, but that HIMA and Union Carbide could better estimate usage allocations, we estimate that between 9.8 and 11.1 million pounds of CFC-12 were used in industrial applications, and between 1.9 and 3.2 million pounds were used in hospitals and institutions in 1976. Since the emissions are prompt, these values also represent the 1976 emissions levels.

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[1] DuPont (1978a), p. VI-35.

The market for CFC gas sterilization appears to be closely linked to the market for presterilized disposable medical and surgical equipment. Industry sources expect this market to grow at about 9.5 percent per year between 1974 and 1985.[4] Applying this same growth rate between 1985 and 1990 leads to an estimate of between 35 and 40 million pounds of industrial CFC-12 use and emissions in 1990, in the absence of controls. If the market for disposables increases as rapidly as forecast, the need for gas sterilization in hospitals and institutions might not grow. Industry sources estimate that 1990 hospital use of CFC-12 will remain at or near the 1976 level.

### Liquid Fast-Freezing Systems

About 10 years ago, DuPont developed a specialized freezing system, called LFF, in which the object to be frozen is placed in direct contact with a purified grade of R-12. The low temperature of the refrigerant causes extremely rapid freezing of the product. Moreover, the liquid refrigerant boils as it comes into contact with the warm product, and the resulting physical agitation causes separation of the objects, allowing them to be individually quick-frozen. Today, LFF systems are used to freeze berries, cob corn, raw shrimp and clams, and meat patties.

The LFF equipment is extremely efficient in recycling the R-12 for repeated use, which minimizes the amount of R-12 that must be purchased to freeze a given volume of food. However, all the R-12 that is used is ultimately emitted to the atmosphere.

Emissions from the LFF process occur in three ways: through evaporation, through dragout, and during cleaning of the machine. Even though both the infeed and outfeed conveyors are covered and inclined, evaporation losses occur at each end of the machine, propelled in part by the movement of the conveyor belts. Dragout emissions occur because a certain amount of the refrigerant adheres to the product and vaporizes upon contact with the relatively warm outside air. When the machine is shut down either for periodic cleaning or production runs, some of the vapor cannot be condensed and is lost. In practice, refrigerant consumption rates vary widely and are influenced by the characteristics of the product being frozen,[5] by the care with which the equipment is operated, and by the operating schedule.

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[2] Letter from Lory A. Crisorio, Union Carbide Corporation, August 14, 1978.

[3] HIMA (1978), p. 2.

[4] A recent study for the FDA reportedly projects future growth of hospital demand for disposable products of all kinds at 20 percent per year.

LFF systems are used for perhaps two percent of the total frozen food market. The closest alternatives to LFF are cryogenic and cryogenic/mechanical systems utilizing liquid nitrogen and carbon dioxide, which account for perhaps four percent of the total frozen food market. LFF and cryogenic systems are both more costly than conventional mechanical systems and thus are used only for food products with which they produce superior results.

In recent years, penetration of LFF systems into the cryogenic and cryogenic/mechanical markets has greatly increased. Much of the penetration has been motivated by the superior economics of the LFF systems, which are discussed in more detail below. In addition, LFF users state that the system reduces product handling and thus increases cleanliness and reduces damage; it also causes less dehydration, thereby preserving product weight and value;[6] moreover, because LFF systems are more compact, they require less space for freezing facilities.

The only formal attempt to project future LFF consumption has been made by DuPont.[7] Table 3.H.1 presents these projections as well as the estimated maximum market potential of the LFF process, i.e., the opportunity for penetration of the cryogenic market.

Table 3.H.1

R-12 USE IN LIQUID FAST FREEZING
(Millions of pounds)

| Markets | 1976 (actual) | 1980 (forecast) | 1985 (optimistic forecast) | Maximum Estimated Market Potential |
|---|---|---|---|---|
| Fruit and vegetable | 3.6 | 4.3 | 5.5 | 7.0 |
| Seafood | 1.0 | 1.2 | 1.5 | 2.0 |
| Meat | 1.0 | 3.5 | 9.0 | 17.0 |
| Specialty (long egg, extruded foods, etc.) | 0.4 | 1.0 | 2.0 | 3.0 |
| Total | 6.0 | 10.0 | 18.0 | 29.0 |

SOURCE: DuPont (1976), Exhibit 1, which describes the detailed assumptions underlying these projections.

DuPont describes its forecast for 1985 as "optimistic." It assumes that both the fruit and vegetable and the seafood markets will have matured with regard to LFF system use. Information provided by industry sources tends to confirm DuPont's estimates in these markets. The greatest increase in LFF use, according to Table

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[5] DuPont notes that with a few exceptions, freezant consumption per pound of frozen food should be invariant with respect to the type of food, provided equipment features and operating practices are held constant.

[6] Lower hydration losses are reflected in the economic comparisons among alternative freezing systems as described below.

[7] DuPont (1976), Exhibit 1.

3.H.1, is in the raw and cooked frozen meat market, for which the DuPont estimates anticipate greatly increased penetration of the cryogenic market. This is a reasonable expectation, since liquid nitrogen and carbon dioxide require a great deal more energy than R-12 to produce and transport, and thus their prices should rise more rapidly as fuel costs increase. However, individuals familiar with both types of systems claim that LFF systems are not gaining as much of this market as was once expected. If it were assumed that LFF consumption would grow only at the rate of frozen meat production, which has been projected at 7.4 percent per year for the near future,[8] LFF consumption for meat products would be only 1.9 million pounds by 1985, instead of the nine million pounds shown in Table 3.H.1, and projected total LFF use in 1985 would be 10.9 million pounds.

These projections of use and emissions ignore potential improvements in refrigerant usage rates, and as a result they may be too high. All the food processing firms we interviewed had modified their operations (and sometimes rebuilt their LFF freezers), thereby achieving reductions in refrigerant consumption.[9] All were giving special attention to proper training of operators, and all were actively looking for additional means of conservation.

It is difficult to project just how successful such conservation measures might be in reducing future LFF consumption. However, even if refrigerant utilization rates improve at only one percent per year over the nine-year period from 1976 to 1985, the figures shown for 1985 in Table 3.H.1 would be reduced by nine percent. If utilization rates were to improve by five percent per year, 1985 usage could be reduced by 37 percent. Table 3.H.2 summarizes the potential effects on R-12 consumption of alternative degrees of conservation improvement. DuPont indicates that conservation improvements of one percent are probably feasible but that a five percent annual improvement is unlikely under current economic conditions.

LFF is, and will probably remain, a specialized CFC application, whose use will be limited to cases where its superior results offset its higher costs relative to mechanical systems or where the process is a lower-cost alternative to another specialty freezing system. While it is difficult to forecast future LFF consumption, use and emissions levels may fail to reach DuPont's optimistic estimate of 18 million pounds by 1985. Our projection of 15 million pounds in 1990 assumes that conservation improvements will result in a use of 9.9 million pounds in 1985, but that fuel cost increases will favor LFF, causing its use to grow at nine percent per year through 1990.

## Other Products

**Bromofluorocarbon Fire-Extinguishing Agents.** There is some indication that the bromofluorocarbons, which include Halon 1211 and Halon 1301, may be as much as 10 times as effective as chlorofluorocarbons in decomposing ozone. Hence, we mention these chemicals here even though they are not CFCs.

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[8] *Quick Frozen Foods*, (1976), p. 33. DuPont points out that the market for specialty freezing of meats is limited to certain items, but the only available projection is for all frozen meats.

[9] Equipment modifications are often motivated by the desire to increase equipment capacity. Larger capacity equipment tends to have lower freezant consumption rates in general, and increases in capacity often solve overloading problems that contribute to high freezant consumption rates.

Table 3.H.2

EFFECT OF REFRIGERANT CONSERVATION MEASURES ON POSSIBLE FUTURE LFF CONSUMPTION RATES

| Conservation Level | R-12 Consumption in 1985 (millions of pounds)<br>DuPont "Optimistic" Estimate | <br>Alternative Estimate |
|---|---|---|
| Neglecting refrigerant conservation | 18.0 | 10.9 |
| Consumption rates reduced 1 percent per year | 16.4 | 9.9 |
| Consumption rates reduced 5 percent per year | 11.3 | 6.9 |

SOURCE: Table 3.H.1. See text for explanation of alternative estimate.

Halon 1211 is employed in a variety of hand-held fire extinguishers and by some Air Force "rapid intervention" crash trucks. Halon 1301 is used in "total-flooding" systems which protect computer rooms, telephone exchanges, and other high-value spaces. The speed of fire containment and lack of residue after discharge compensate for the extremely high cost of using bromofluorocarbons in these situations. The mechanism by which these compounds extinguish a fire is not fully understood, but it is generally believed to involve the chemical interruption of the combustion chain.

The use of Halon 1301 depends largely on the number of fire extinguishers manufactured each year and the average system charge. DuPont estimates that by early 1978, 10,000 of these systems had been installed.[10] Industry sources indicate that widespread installation of total-flooding systems began in about 1972. Therefore, we have assumed that prior to 1972, the number of installed systems was zero, and that the number increased linearly from that date, reaching a stock of 10,000 units by the end of 1977.

Estimates of future rates of installation of Halon 1301 systems vary widely, as do estimates of average system charges. As a reference case, we have chosen a growth rate for system installations of 25 percent per year through 1980 but falling to 10 percent thereafter, and an average system capacity of 600 pounds.

There are five sources of emissions from Halon 1301 systems. During the filling of installed systems, a small amount, estimated at 0.5 percent of consumption, is emitted through piping connections and other seals. Another small amount occurs as leakage. Our estimate of the magnitude of this loss is 0.0000781b, where b is the amount of Halon 1301 in the stock of installed systems. The third source of emissions occurs during tests in which an installed Halon 1301 system is required to hold a specified gas concentration in the area to be protected for a given period of time. We have assumed the testing frequency to be 10 percent of the installed systems, with only half of the testing performed with Halon 1301.[11] Some systems occasionally malfunction, inadvertently discharging their charge. We estimate the probability of this at one percent per system per year. The probability of a discharge due to an actual fire is estimated to be half that of inadvertent discharges.

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[10] DuPont (1978a), p. IV-6.

Table 3.H.3 presents estimates of 1977 and 1990 emissions, consumption, and stocks of Halon 1301. Consumption includes the initial charge for new units plus emissions from all sources, while the bank includes the stock of all units with their contained charges.

Table 3.H.3

ESTIMATED HALON 1301 CONSUMPTION, EMISSIONS, AND BANK[a]
(Pounds)

| Emissions Source | 1977 | 1990 |
|---|---|---|
| Filling and servicing | 6,695 | 16,672 |
| Normal leakage | 375 | 2,158 |
| Testing | 60,000 | 138,150 |
| Inadvertent discharge | 48,000 | 276,324 |
| Discharge during fire | 24,000 | 138,162 |
| Total emissions | 139,070 | 571,466 |
| Total consumption | 1,339,070 | 3,334,466 |
| Bank[b] | 6,000,000 | 30,395,400 |

[a] Calculations explained in text.

[b] This figure is the total amount of Halon 1301 contained in all systems installed prior to and including the indicated year. Since the scrappage rate has been assumed to be zero, this might overestimate the true bank.

The values in Table 3.H.3 indicate clearly that emissions are only a small fraction of total consumption, about 10 percent in 1977 and approximately 17 percent in 1990. According to the estimates, the Halon 1301 bank in 1990 will increase significantly—to about five times the 1977 level.

Data on Halon 1211 use and emissions are not available, but are likely to be lower than for Halon 1301.

**Single-Station Heat Detectors.** A small amount of CFC-12 is employed in fire warning devices known as single-station heat detectors.[12] These devices consist of a container of CFC-12, a heat-sensitive actuating device, and a horn through which the CFC, liberated by the actuating device, escapes.

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[11] The other half of the testing is done with CFC-12.

[12] This product is not the same as the now familiar smoke detector, and it is used in situations where heat rather than smoke is likely to be a primary indicator of fire. Smoke detectors do not use CFCs.

There are no generally accepted estimates of either the current rate of production of these devices or the total number of units presently in the field. Use of CFC-12 for this purpose has been estimated at between 150,000 and 300,000 pounds in 1975. Assuming an average unit charge of 12.5 ounces, the CFC-12 was used to fill between 192,000 and 384,000 units that year.

Single-station heat detectors have been marketed for about 25 years. If it is assumed that output in the first year of production (which we take to be 1950) was modest, say 1,000 units, then an average annual growth rate of about 25 percent would yield a 1975 production level of about 265,000 units, slightly below the midpoint of the range estimated above. Applying the same rate of growth through 1977 leads to production in that year of about 414,000 units and a stock of approximately 1.65 million units.

Future production levels are highly uncertain. As an upper bound, we assume that a 25 percent growth rate might continue through 1990. This would result in a unit production level of about 7.5 million units for that year. If all units are filled with 12.5 ounces of CFC-12, consumption by 1990 would total about six million pounds.

Emissions from single-station heat detectors are extremely small. Production losses may be only a few thousand pounds, and the number of inadvertent discharges is apparently so small as to be treated here as negligible. The final emissions source, discharge during fire, is estimated at between 0.1 and 0.3 percent per year of stocks. We use the 0.3 percent value, again as an upper bound.

Table 3.H.4 presents the estimated consumption, emissions, and bank of CFC-12 in these units for 1977 and 1990. Consumption includes the initial charge, while the bank represents the contained charges of all units manufactured prior to and including the current year. One manufacturer of these units, Falcon Safety Products, has recently marketed a smaller, less-expensive unit which holds only two ounces of CFC-12. If all heat detectors manufactured between 1977 and 1990 were of this type, emissions during fires in 1990 could be reduced from the 87,000 pounds estimated in Table 3.H.4 to about 17,000 pounds.

Table 3.H.4

ESTIMATED CFC-12 CONSUMPTION, EMISSIONS, AND BANK IN SINGLE-STATION HEAT DETECTORS[a]

(Millions of pounds)

| Item | 1977 | 1990 |
|---|---|---|
| Emissions | 0.004 | 0.087 |
| Total consumption | 0.327 | 5.971 |
| Bank[b] | 1.289 | 29.086 |

[a] Calculations explained in text.

[b] Estimated lifetimes of the units are from 30 to 50 years. We have ignored scrappage, so the bank overestimates the true stocks.

**Other Warning Devices.** There are a number of warning devices which operate on a principle similar to that of the single-station heat detector. These include personal protection alarms, signal horns, boat horns, intruder alarms, and bicycle alarms, all of which utilize CFC-12.

To the extent that these devices are purchased but not immediately used, they represent some degree of CFC banking. However, in the absence of data on such storage, we assume they are prompt emitters.

Falcon Safety Products estimates total industry consumption of "products like ours" (including single-station heat detectors, other warning devices, a product called "Dust-Off," and boat horns) at 1.25 to 1.75 million pounds per year. Assuming that about 225,000 pounds of CFC-12 per year is used for single-station heat detectors, approximately 1.2 million pounds remains for use in personal protection devices, Dust-Off, and boat horns. Our best estimate is that less than one million pounds of CFC-12 per year is used in and emitted from warning devices. Projections of future CFC-12 use for this application are not available.

**Dehumidifiers.** Dehumidifiers are simple hermetic systems that use R-12 to remove moisture from the air in the home. IR&T estimates that shipments of dehumidifiers totalled 510,000 units in 1976. Based on shipments from 1957 through 1976, the projected shipments for 1990 are 909,000 units. The average charge of a dehumidifier is estimated to be 0.9 pounds, based on an estimate in a previous EPA study of 0.84 pounds and a major producer's estimate of 14 to 15 ounces per machine. The average lifetime of a dehumidifier is about 20 years.

The emissions characteristics of dehumidifiers are similar to those of refrigerators and freezers. Manufacturing emissions are estimated at eight percent of initial charge in 1976, declining to seven percent by 1990. Leakage and servicing emissions are estimated to be 0.2 and 1.5 percent of refrigerant stocks, respectively. Disposal emissions are calculated by IR&T on the assumption that 96 percent of the charge remains at the time of disposal.

Table 3.H.5 presents data on estimated use, emissions, and bank of R-12 for dehumidifiers in 1976 and 1990. Purchases were calculated by summing initial charges and all emissions except those at disposal.

Table 3.H.5

ESTIMATED USE, EMISSIONS, AND BANK OF R-12 FOR DEHUMIDIFIERS[a]

(Millions of pounds)

| Item | 1976 | 1990 |
|---|---|---|
| Use | 0.616 | 1.121 |
| Emissions | 0.333 | 0.757 |
| Bank | 7.069 | 14.319 |

[a] Calculations explained in text.

**Pressurized Blowers and Drain Cleaners.** These products use pressure from CFC gas to displace lint or dust from a surface or free a clogged drain.

There are at least three pressurized blowers on the market. All use CFC-12, which is emitted promptly during use. It is estimated that current use and emissions in these devices is less than one million pounds.

At least two products using CFCs for cleaning drains are presently marketed. Current CFC usage in these drain openers is estimated to be 950,000 pounds of CFC-12 and 53,000 pounds of CFC-114. Emissions from these products are also prompt.

No projections of CFC use in either device are available.

**Skin Chillers and Presurgical Skin Cleaners.** Small amounts of CFC-11, CFC-12, and CFC-114 are used in vapor form to chill skin as a form of topical anesthesia. CFC-113 is a solvent used in operating rooms to remove oils from the skin, reducing the risk of infection and facilitating adhesion of surgical drapes to the skin.

One estimate places the combined CFC usage in skin chillers at 23,000 pounds annually.[13] About 100,000 pounds of CFC-113 per year is used in operating rooms to remove oils from the skin.[14] Both types of products can be considered prompt emitters. Again, there are no projections of future use of CFCs in these markets.

**Whipped-Topping Stabilizer.** The addition of CFC-115 to whipped topping allows less butterfat content, prevents the last 20 percent of the topping from becoming watery, and provides the stability necessary to inhibit sagging after the topping has been dispensed.

CFC-115 is used in about one-fourth of the 100 million whipped-topping units produced annually. Current use and emissions of CFC-115 from this source are estimated at less than 100,000 pounds per year. Estimates of future market growth are not available.

**Coal Cleaning.** Chlorofluorocarbons are used to recover hydrocarbon values from coal. In one process, raw coal is placed in a CFC-11 bath, causing the less dense coal to float and the more dense refuse material to sink. The coal is removed from the liquid surface, while the refuse is recovered separately and used as dry land fill.

In this application, CFC emissions are prompt. Two alternative estimates of emissions rates are available. The first, made by Ostica Industries,[15] places emissions at 0.05 pounds of CFC per ton of raw coal processed, while the second, made by McNally Corporation,[16] estimates the rate at two pounds of CFC per ton of coal cleaned. Current coal production for which this process is used is less than one million tons, which implies that CFC-11 use and emissions could vary between 50,000 and two million pounds; we adopt one million pounds as the current estimate.

Ostica Industries' "optimistic" projection of CFC use is 3.5 million pounds in 1989. We use this figure for the 1990 use and emissions estimates.

**Trucking Refrigeration.** This category includes refrigeration for trucks, air conditioning in buses, and air conditioning in rapid-transit vehicles other than buses. Since the late 1960s, there has been virtually no refrigerated transport by rail.

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[13] EPA (1977a), pp. 4-67 through 4-73.

[14] DuPont (1978a), p. IV-6.

[15] EPA (1977a).

[16] EPA (1977a), pp. 4-67 through 4-73.

Refrigerated trucks are used for intracity deliveries of perishables, including neighborhood deliveries of dairy products. Industry sources estimate that approximately 5,000 refrigerated trucks are manufactured annually and that the average charge of the refrigeration unit is nine pounds of R-12. Thus, about 45,000 pounds of R-12 are used annually to charge these refrigeration devices. Over-the-road trailers for intercity transport of perishables use an average charge of 17 pounds per unit, and approximately 17,000 units are produced annually. Thus, about 289,000 pounds of R-12 is used annually to charge these larger trucking refrigeration units.

Annual production of air conditioning systems for intracity buses is currently about 4,000 units, while about 1,000 units are produced annually for intercity buses. Industry sources estimate that 75 to 85 percent of these systems are charged with R-22, the remainder with R-12. At an average initial charge of 15 pounds per unit, this application would account for 15,000 pounds of R-12 use and 60,000 pounds of R-22 use per year. Current trends favor R-22 because it requires a smaller compressor and has larger capacity parameters.

Other rapid-transit systems also use air conditioning systems charged with R-22. Initial charges of these units amount to less than 10,000 pounds per year, at current production levels of 500 cars annually.

These applications account for less than half of the 1973 mobile vehicle refrigeration system shipments recorded by the *Census of Manufactures.* We cannot account for the discrepancy, but it seems likely that the 69,000 shipments recorded by the Census include a large number of very small units. Moreover, even if we double the R-12 usage figures cited above, the total use for initial charges in this application category remains very small, less than one million pounds. There are no data on future growth for this application.

As in other refrigeration applications, emissions from trucking refrigeration depend on the size of the bank. There are no data on the bank of air conditioning systems for buses or other rapid-transit vehicles, but the American Trucking Association and the *1972 Census of Transportation* indicate that there are over 100,000 city delivery trucks and nearly 125,000 over-the-road trailers currently in use. The bank of R-12 implied by these stock estimates is 3.1 million pounds. Without information on the emissions rates from the bank, we cannot estimate annual emissions, but it is clear that such emissions must be very small relative to those in other product areas covered by this study.

**Incipient and Specialty Applications.** CFCs are used in extremely small amounts for cleaning and lubricating aircraft parts; chilling electronic parts; drying numismatic blanks, coins and medals; propelling air brushes; removing chewing gum; propelling roach and insect killer; cleaning and lubricating electric shavers; treating books, prints, and documents; cooling in the gaseous diffusion process for uranium enrichment; and as a refrigerant in home water coolers and ice makers. CFC use and emissions data for these applications are largely unavailable, so we have not included them in this study.

### Use and Emissions Summary

Table 3.H.6 summarizes CFC use and emissions estimates for 1976 and 1990. Where 1990 use estimates were not available for a product area, we have assumed an annual growth rate approximately that of the same CFC in the major product areas described in previous sections.

Table 3.H.6

USE AND EMISSIONS OF FLUOROCARBONS IN MISCELLANEOUS PRODUCTS[a]
(Millions of pounds)

| Product | Fluorocarbon | 1976 | | 1990 | |
|---|---|---|---|---|---|
| | | Use | Emissions | Use | Emissions |
| Sterilants | CFC-12 | 13.0 | 13.0 | 40.0 | 40.0 |
| LFF | CFC-12 | 6.0 | 6.0 | 15.0 | 15.0 |
| Fire extinguishers[b] | Halon 1301 | 1.2 | 0.1 | 3.3 | 0.6 |
| Heat detectors[c] | CFC-12 | 0.3 | (d) | 5.9 | (d) |
| Warning devices | CFC-12 | 0.9 | 0.9 | 1.7[e] | 1.7[e] |
| Dehumidifiers[f] | CFC-12 | 0.6 | 0.3 | 1.1 | 0.8 |
| Blowers and drain cleaners | CFC-12 | 1.3 | 1.3 | 2.4[e] | 2.4[e] |
| | CFC-114 | (d) | (d) | 0.1[e] | 0.1[e] |
| Skin chillers and cleaners | CFC-11 | (d) | (d) | (d) | (d) |
| | CFC-12 | (d) | (d) | (d) | (d) |
| | CFC-113 | 0.1 | 0.1 | 0.2[e] | 0.2[e] |
| Whipped topping | CFC-115 | 0.1 | 0.1 | 0.2[e] | 0.2[e] |
| Coal cleaning | CFC-11 | 1.0 | 1.0 | 3.5 | 3.5 |

[a] Calculations explained in text.

[b] The bank of Halon 1301 in fire extinguishers was about five million pounds in 1976 and could reach 30 million pounds in 1990.

[c] The bank of CFC-12 in heat detectors was about 1.0 million pounds in 1976 and could reach 29 million pounds in 1990.

[d] Less than 100,000 pounds.

[e] Assumes the same average growth rates as for major product areas using the same CFC.

[f] The bank of CFC-12 in dehumidifiers was about seven million pounds in 1976 and could reach 14 million pounds by 1990.

## INDUSTRY AND MARKET CHARACTERISTICS

### Sterilants

As discussed earlier, sterilization is performed either in hospitals and institutions themselves or in industrial sterilization firms. DuPont estimates that there are approximately 3,000 hospital sterilizers presently in service equipped to use

12/88, and that an additional 3,000 "desk type" gas sterilizers are in use in clinics, doctors' offices, and hospitals, 25 percent of which use ethylene oxide/CFC blends. The value of the present stock of hospital/institutional sterilizers is estimated at between $38 million and $64 million.

DuPont estimates that there are about 200 industrial gas sterilizers using 12/88,[17] while Vacudyne Altair, a major manufacturer of industrial sterilizers, places the number "in excess of 400,"[18] and a source at Pennsylvania Engineering estimates that the number is closer to 1,000. Estimates of the size of the typical industrial sterilization unit range from 200 to 850 cubic feet. The total investment in industrial sterilizers is estimated at between $20 million and $40 million.

We estimate that sterilization costs account for between seven and 15 percent of the total cost of disposables.

### Liquid Fast-Freezing Systems

As discussed earlier, perhaps two percent of the total frozen food market uses LFF. DuPont estimates that there were about 32 LFF systems in existence as of late 1978, but some users believe that DuPont does not have a full count of custom-made systems. System suppliers expect to sell three to five units per year in the future.

Information provided by firms that use LFF systems indicates that LFF-frozen food sales account for between 0.002 and 50 percent of total corporate sales. The smaller figure was reported by a large food processing firm that had recently installed an LFF system to freeze a single product in its broad line. The company also estimated that between 12 and 15 workers, about 0.001 percent of its total employment, would be affected by regulation of LFF.

A more typical user is a seafood processing firm, which reported that LFF-frozen products account for 50 percent of its revenues, and that of its total of 360 workers, 110 would be directly affected and 25 indirectly affected if LFF use had to be discontinued. Another firm, a small specialty packer of fruits and vegetables, reported that approximately 50 percent of its revenues are derived from LFF-frozen products, and that 50 "regular" and 350 "seasonal" workers would be affected if controls were placed on LFF.

The largest current user of LFF is Green Giant (Minnesota), which has five systems in operation at four plants and values the investment in these systems at $3.1 million. Its LFF product is frozen cob corn, for which at least one of its competitors uses an air-blast (cryogenic/mechanical) system. Other firms that have identified themselves as LFF users include General Foods (New York), Booth Fisheries (Chicago), National Sea Products (Florida), Stayton Canning Company Cooperative (Oregon), Flavorland Foods (Oregon), Wilson Foods (Oklahoma), and Heying Foods (Iowa).

A second group of firms which stands to be affected by controls on LFF is freezing-equipment manufacturers. Although a few custom-made one-of-a-kind units are produced, the principal supplier of LFF freezing equipment at present is Frigoscandia Contracting, an international corporation which manufactures a full line of freezing equipment. Frigoscandia's U.S. subsidiary reports that LFF equipment accounts for less than 10 percent of their current sales and that they do not expect this percentage to increase. Another major manufacturer of LFF systems is Lewis Refrigeration of Woodinville, Washington.

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[17] DuPont (1978a), p. IV-6.

[18] Letter from Harvey Markinson, Vice President-General Manager, Vacudyne Altair, November 2, 1978.

### Other Applications

**Bromofluorocarbon Fire-Extinguishing Agents.** Halon 1301 is supplied by two companies, DuPont and Forex Chemical Corporation. Because of the high cost of bromofluorocarbons, estimated at between $2.50 and $3.50 per pound wholesale, Halon 1301 systems are not likely to be adopted for uses other than in high-value areas such as computer rooms. A moderate increase in the price of Halon 1301 would probably not prevent sales of the systems in such high-value situations. The suppliers of the chemical sell exclusively to manufacturers of fire-protection equipment and to the U.S. government.

**Single-Station Heat Detectors.** Single-station heat detectors are manufactured primarily by two firms, Falcon Safety Products and Evergard. However, other manufacturers may exist.

A new model has recently been marketed exclusively by Falcon which is smaller and less expensive than the traditional model and retails for about $19 rather than $70 to $90. Because the new device requires less CFC-12, Falcon would have a cost advantage over the other manufacturers of heat detectors if the price of CFC-12 were to rise. However, the cost of the CFC-12 is very minor compared with the cost of the heat detector itself. At the current price, the cost advantage from charging one unit with two ounces instead of 12.5 ounces is about 27 cents. Even if the price of CFC-12 were to increase tenfold, manufacturers of the large devices would find that their production costs would rise by only about $3 per detector.

**Other Warning Devices.** Falcon Safety Products markets a "personal protection and signal horn" under the trade name Sound 911. Other firms (not identified here) market a variety of similar devices for use as boat horns, intruder alarms, and bicycle alarms.

**Dehumidifiers.** Neither IR&T nor Rand has data on the manufacturers of dehumidifiers.

**Pressurized Blowers and Drain Cleaners.** Most pressurized blowers are marketed by two firms, Falcon Safety Products, which calls its product Dust-Off, and Century Laboratories, which uses the trade name Omit Plus. A third firm, Miller-Stephenson, also provides a product of this type, which it calls Aero Duster.

Drain cleaners are also marketed primarily by two firms, Glamorene, which calls its product Drain Power, and the Drackett Company, which calls its product Drano. From sales data, we are able to infer that Glamorene's market share is about 40 percent. CFC-propelled power drain cleaners comprise a small share of the total drain cleaning market, which includes several chemical drain openers.

**Skin Chillers and Presurgical Skin Cleaners.** We are aware of no data that provide economic characteristics of the firms engaged in marketing these products.

**Whipped-Topping Stabilizers.** CFC-115 represents about one percent of the net package weight of the 25 million units of CFC-stabilized whipped toppings produced annually. There are 15 firms that produce these whipped toppings; some available from Vacudyne Altair. This unit, which costs $125,000 installed, recovers 60 to 80 percent of vented sterilant gas, replaces any ethylene oxide lost through absorption by the material being sterilized, and reinjects the sterilant gas into the sterilizer. The producer of the unit claims it is cost-saving at current sterilant gas prices; however, only one such unit is currently being operated, and that unit is in a facility owned by its developer. We do not have sufficient information to determine the prices of sterilant gas at which the recovery unit would become more widely used, though it is likely that larger sterilization units would begin recovery at lower gas prices than smaller units. If the use of such units became widespread beginning in 1980, cumulative emissions (and cumulative use) of CFC-12 from this application would fall by at least 157 million or as much as 209 million pounds between 1980 and 1990.

The second option involves shunting waste gas from one sterilizer to another. This procedure would have a relatively low cost to any firm having more than one sterilization unit, but the gains in terms of emissions reductions are unknown. The observation that the procedure is not used might indicate that the costs of coordinating sterilization cycles are sufficiently high to outweigh the gas savings, at least at current gas prices.

The third option is increasing the length of the sterilization cycle to permit lower gas levels per cycle. If this is technically feasible, its economic advantages depend on (1) its effects on operating costs and (2) whether firms have sufficient capacity to permit lower throughput rates without sacrificing levels of output.

For hospitals and institutions, which use smaller sterilization units, the use of less gas per unit means that the preceding options are less likely to be economical at any given gas price. One company offers an alternative sterilization system ("Sterijet") appropriate for hospital use that uses CFC-11 instead of CFC-12 and requires much less gas to perform the sterilization function. Pursuit of this option would require replacement of the stock of hospital equipment, currently valued at $38 million to $64 million, and would have relatively little effect on emissions of CFC-12 because hospitals and institutions use fairly small amounts and their use is not expected to grow much over the next decade.

Industry sources vary in their opinions of the promise offered by the foregoing options, just as they vary in their estimates of current sterilant use and projected emissions. Opinions are far more uniform concerning another approach to the emissions problem: Virtually everyone we interviewed agreed that substitution of alternative sterilant gases or techniques for 12/88 is a bad idea. Sterilization by steam, the principal alternative in use by hospitals and institutions, is relatively inexpensive and safe, but it is incompatible with some of the materials from which modern medical devices and supplies are made. Both of the alternative sterilant gases, pure ethylene oxide and ethylene oxide/carbon dioxide blends, are widely criticized, the former for its toxicity and flammability, the latter for its inconvenience (due to high cylinder pressures) and because it is relatively inefficient.

We suspect that economics plays a much larger role in the stated preferences for 12/88 than is readily apparent from the statements of industry sources. And if economics is an important driving force behind the growth in 12/88 use, policy action to modify the economics of the situation can be an important driving force to reduce emissions of CFC-12 in this application.

No industry source has offered a detailed comparison of the costs of using alternative sterilant gases, even for a single, well-defined case. One source made the general comment that pure ethylene oxide is far more costly to use than 12/88, but this appears to conflict with the comment by another source that some very large industrial users find the cost savings from using pure ethylene oxide sufficient to offset the added costs of insulating chambers required to safeguard against the flammability hazard.

Although the carbon dioxide blends are not new, they account for a far smaller share of the sterilant gas market than does 12/88 (as indicated by a survey conducted by the HIMA). This alone suggests that current economic conditions favor the use of 12/88 over the carbon dioxide blends. Furthermore, modest changes in sterilization economics are not likely to lead to substitution of these blends for 12/88 by current users because they require different equipment.

In contrast, substitution of pure ethylene oxide might be induced by higher 12/88 prices. At present, about one-fourth of the sterilant gas used for industrial sterilization is pure ethylene oxide, and substitution of the pure gas for 12/88 does appear feasible if certain modifications are made to existing units and if they are enclosed in an insulation chamber.

In the absence of data necessary to predict how 12/88 users would respond to higher gas prices, we have treated this demand for CFC-12 in our basic analysis as though it were perfectly inelastic. However, the foregoing discussion strongly indicates that CFC emissions in this application could be reduced substantially and that higher CFC prices could motivate such reductions. The analysis of economic incentives in Sec. IV shows the effects on the policy outcomes of assuming that price increases could motivate use of some combination of the preceding emissions-control options that would reduce CFC use in this application by 80 percent.

It is also possible that a selected set of mandatory controls could reduce these emissions by up to 80 percent without limiting the availability of sterilized medical supplies. If so, and if the controls could be implemented soon, the cumulative emissions reduction between 1980 and 1990 from this product area alone could increase the reductions under the benchmark control candidates by nearly one-third. This suggests that if mandatory controls rather than economic incentives were used to limit CFC emissions, further technical and economic assessment of the options in this product area would be very valuable.

### Liquid Fast-Freezing Systems

Emissions of R-12 from LFF applications could be reduced by system improvements to reduce loss rates or by limitations on the use of LFF systems. No specific design improvements have been identified as being particularly effective in reducing emissions, because the systems are already designed for maximum recycling of vapor losses. Instead, the major improvements in emissions seem to be related to using systems of the proper capacity to prevent overloading and to adopting good operating practices. Since operation is highly seasonal in this application, overloading may not be uncommon and restrictions on loading rates for various equipment might be possible, given that there are few sites to be monitored. Operating practice standards do not appear enforceable, however, because they would require continual monitoring. In the absence of data on freezant consumption rates under actual operating conditions, it is not possible to predict the emissions reductions achievable under loading-rate controls.

Restrictions that forbid production of new sources or expansion of existing ones would reduce 1990 emissions by perhaps five million pounds. Such restrictions would also generate significant excess profits for existing LFF users because the alternative specialty systems appear to be far more costly to use and would cause some loss of business (at about $400,000 per system and three to five new systems per year) to LFF system suppliers.

Restrictions that eliminate all use of LFF would impose substantial costs on existing users. Green Giant estimates that replacing their existing systems would take three to five years and would cost in excess of $6 million; and the construction costs for new facilities to house the new systems would increase that figure to $21 million. Green Giant claims it would discontinue production if LFF use were prohibited because it lacks the capital to make the conversion.

Industry sources have identified several disadvantages of eliminating the use of LFF, including increased consumer prices for similar products produced with alternative systems, reduced product quality, and the elimination of certain products (e.g., extruded eggs) that cannot be frozen acceptably by other systems.

Another disadvantage would be increased energy utilization. Although air-blast (cryogenic/mechanical) and liquid-nitrogen systems use less energy to freeze a given volume of food, the freezant use rates for carbon dioxide and nitrogen are much higher than those for LFF and their production and transport require greater amounts of energy. One source estimates that liquid nitrogen requires 9 to 10 times the Btus of LFF to freeze a pound of food, while carbon dioxide requires 17 to 20 times the Btus. To the extent that current or future energy prices do not reflect their real resource cost, a simple comparison of the costs of alternative systems does not reveal the true cost advantages of LFF.[20]

Available evidence strongly suggests that economic incentives could be used to reduce CFC emissions from LFF systems, though the precise relationship between LFF prices and emissions cannot be ascertained. Illustrative examples of the production costs of different systems, provided by various industry sources, including DuPont and Frigoscandia, are presented in Appendix B. The examples differ in assumed food type, loading rates, equipment sizes, and other features, and assumed current prices of LFF vary from 45 cents to 57 cents per pound. In most cases, the examples provide two-way comparisons between LFF and liquid-nitrogen systems. One set of illustrations refers to air blast as well, and the air-blast estimates are shown for the one situation (freezing raw meat patties) where air blast is indicated to be the least-cost of the three methods, and for a second situation (freezing shrimp) where air blast is less costly than liquid nitrogen.

The prospective user of LFF is concerned with overall operating cost per pound of food. If this cost is the only factor, the cost examples indicate that prospective users would become indifferent between LFF and a competitive system if the price of LFF freezant rose by varying amounts, depending on specific expected operating conditions. In one example, an increase in the price of LFF freezant of 97 cents per pound would make its use equal in cost to that of the alternative system; in another, the crossover price increase would be $1.50. Both of these price increments are in the upper range of the changes considered in this study. If there are cost-saving methods for still greater reductions in freezant use, the price increments required to dissuade LFF use would be larger, while if the user anticipates some overloading with LFF (but not with the alternative systems), the necessary price increment would be smaller.

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[20] Some industry sources have converted the Btu estimates into costs by multiplying by the current price of energy per Btu. This is an incorrect procedure for calculating the energy cost of eliminating LFF systems. The current prices of liquid nitrogen and carbon dioxide already cover the energy expenses for their production and transportation, so a comparison of freezing costs between LFF and the alternatives already embodies the energy expenditure differentials among them.

In the absence of information on the conditions under which producers might expect to be operating, we cannot tell how much LFF use would be reduced by any of the price increments in the foregoing range. Moreover, except for the one case in which the air-blast system appears to have lower costs, the illustrative examples do not allow us to explain why any new user would choose a system other than LFF. Therefore, it cannot be assumed that changing the LFF price by precisely the indicated amounts is either necessary or sufficient to induce prospective users to choose alternative systems.

The important economic issue for existing LFF users is whether to continue LFF use in the event of a price increase. Since some of their original capital investment is already amortized, the capital loss from discontinuing LFF use is equal to only a portion of the original investment.[21] As long as the LFF-frozen food price continues to allow recovery of variable operating costs, the existing user would retain his LFF system; if the frozen food price is even slightly higher than variable operating costs, the user would be able to continue amortization of the original investment, though at a slower rate. According to the illustrative cost examples, variable operating costs per unit of food frozen with LFF are only 26 to 40 percent as large as the variable operating costs per unit of competing systems. Hence, the available data seem to indicate that existing LFF users would continue to be able to charge competitive prices even if the LFF freezant prices doubled. This is consistent with the comment by one LFF user that a doubling of the LFF freezant price would be passed through to final product consumers in the form of a three to five percent increase in frozen food costs.

Although the basic analysis of economic incentive policies in Sec. IV treats LFF demand for CFCs as though it were perfectly inelastic, there does appear to be some elasticity of demand, particularly among prospective users, in the upper end of the CFC price range under consideration in this study. Therefore, Sec. IV also considers how the overall results of an economic incentive policy might differ in the presence of such demand elasticity.

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[21] For example, Green Giant estimates that its write-off would be $1.75 million, as compared with the original investment amount of $3.1 million.

# IV. ECONOMIC INCENTIVES VERSUS MANDATORY CONTROLS: EMISSIONS REDUCTIONS AND COMPLIANCE COSTS

Together, this section and Sec. V compare various features of economic incentives policies with those of mandatory controls. This section begins with a description of how and why economic incentives function, then develops definitions and methods necessary for comparing incentive strategies with mandatory controls. Finally, it derives four specific economic incentive policy designs, contrasting them with one another as well as with the mandatory controls.

The alternative policies presented in this section are compared in terms of their effectiveness in reducing emissions. Two of the economic incentives policies are designed to achieve the same emissions reductions as the benchmark mandatory controls identified in Sec. I, while two would achieve greater reductions.

This section also compares the effects of the policy alternatives in terms of the sacrifices that must be made by the U.S. economy as a whole in order to reduce CFC emissions between 1980 and 1990. As explained in Sec. II, all policies to limit emissions either directly or indirectly cause increased use of economic resources for emissions-reducing activities (e.g., increased use of equipment to recover and recycle CFCs), thereby reducing the ability of the economy as a whole to produce other goods and services. We have termed the measure of this sacrifice—the dollar value of the resources so engaged—the "compliance cost." Here, we show that (1) compliance costs of mandatory controls differ substantially from those of economic incentives that achieve the same cumulative U.S. emissions reductions; (2) different economic incentive policy designs can yield differences in compliance costs for the same amount of emissions reduction; and (3) economic incentives can be used to exceed the benchmark level of emissions reduction, but compliance costs rise more than proportionately.

Other important differences among policies are examined in Sec. V. There, major policy differences are predicted for the distribution of regulatory costs among industries, firms, and consumers. For economic incentives policies, the distributive outcomes—and their implications for consumer prices, plant closures, and the productivity of capital—depend critically on how the policy is implemented and operated. Section V examines this and other operational aspects of policy, together with a number of other policy concerns.

## HOW ECONOMIC INCENTIVES WORK

Economic incentives strategies operate on a basic economic principle: As CFC prices are raised, industry will seek ways to reduce CFC use in order to avoid higher production costs. Firms may substitute alternative chemicals for CFCs, purchase equipment to recover and recycle CFCs that would otherwise be emitted into the atmosphere, or purchase equipment that limits the rate at which CFCs escape into the atmosphere, thereby prolonging the usefulness of a given amount of them. The product area demand analyses in the preceding sections indicated the CFC prices at which these activities should become cost-effective in various applications. By effectively raising the prices CFC users must pay, economic incentives make emissions reductions cost-effective, and the desired policy outcome is achieved through decentralized decisionmaking by firms without direct monitoring and enforcement.

Two alternative policy mechanisms are available for raising the effective CFC price. One is an excise tax that must be paid by users for each pound of CFC purchased. As with other sales taxes, the CFC seller collects the tax and remits it to the taxing authority. Under a tax system, the user who reduces his CFC purchases reduces his expenses by the amount of the tax as well as by the amount of the CFC supply price. Thus, the cost saving from reducing CFC use is greater than it would be without the tax, and techniques for controlling use and emissions become profitable.

Alternatively, CFC prices can be increased indirectly by restricting the quantity of CFCs available. If a quota is imposed, some mechanism will arise to allocate the reduced amount of CFCs among competing users. If the regulation does not supply an explicit mechanism, the CFC producers must devise one. For example, they might raise CFC prices so that users will reduce their purchases, or they might ration CFCs in some other way, with uncertain consequences for the ultimate effects on emissions. (See Sec. V.)

Instead, the regulatory agency can issue permits for CFC purchases. Users must then buy permits in order to obtain CFCs, and the prices they pay for permits represent an increase in CFC costs. Thus, a permit quota likewise increases the effective price of CFCs and encourages firms to seek ways to reduce their purchases.

Under a permit quota, the regulatory agency establishes a quota for CFC production during a specified period of time, and an amount of permits is released corresponding to the quota. The permit (which is essentially a ration coupon) authorizes a user to purchase a specified amount of any of the regulated CFCs.[1] Upon making a CFC purchase, the user must transmit to the seller the requisite number of permits; the seller then turns the permits in to the regulatory authority to register completion of a CFC sale. The regulatory authority monitors the production and sale of CFCs to assure that sales do not exceed the amounts authorized by the number of permits that have been remitted during each time period.

The permits could be bought and sold among eligible parties to the market,[2] and thus they are described as "marketable" or "exchangeable." This feature is essential because it means that the permits continue to have a market value even after a user has obtained them; a permit holder's consumption of CFCs implies a decision to forgo receiving the sum others would be willing to pay for his permits.

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[1] Some CFC users purchase reclaimed as well as virgin CFC. Since the amount of virgin production is the ultimate determinant of emissions levels, this is the appropriate target for economic incentives policies. The prices of reclaimed CFC should not be increased by regulation, since such action would discourage reclamation activities that may directly reduce CFC emissions.

[2] Section V discusses the matter of eligibility for participation in the permit market. Of course, under a tax policy, users would be allowed to buy and sell CFCs among themselves.

For expositional convenience, we speak as though all CFC users must buy permits or pay taxes for all the CFC they buy. However, the predicted effectiveness of economic incentives in reducing emissions does not depend on this feature. Section V explains how a properly designed implementation plan can achieve the emissions reductions cited below while exempting some users from the policy, granting tax forgiveness for some portions of CFC use, or directly allocating permits without requiring payments for the initial allocation.

The tax rate that would achieve a given reduction in CFC use is equivalent to the permit price that would result if a quota reduced the availability of CFCs by the same amount. Thus, the same reduction in use can be achieved with either taxes or a permit quota, and the effective increase in the CFC price would be the same under both policies.

Taxes and permits do have differences in their operation and implementation. For example, one important distinction results from uncertainty about the estimated demand schedules used to predict permit prices or requisite taxes to achieve a given policy goal. The level of CFC use under a permit system is known with certainty, but the permit price that actually develops might differ from the prediction; under a tax system, the increase in CFC prices is known with certainty, but the expected reduction in use might differ from the prediction. Other operational distinctions between the two types of incentive policies are discussed in Sec. V. For the remainder of the section, however, tax and permit policies are treated as equivalent.

The ultimate goal of policy is to limit or reduce CFC *emissions*, but the tax and permit quota policies examined here achieve this goal indirectly, by reducing CFC *purchases*. This type of incentive policy design is appropriate for several reasons. First, the total level of CFC purchases can be easily monitored. While there are millions of point sources of emissions, there are only a handful of plants that produce CFC. Thus, it is much less costly to administer a quota or tax on CFC sales than on CFC emissions.

Second, reductions in CFC purchases and use closely approximate reductions in emissions. There are very few applications that do not ultimately release all of the CFCs used. In some products, most notably rigid foam insulation, emissions are greatly delayed, but CFC use in these products is quite insensitive to CFC prices. More than 95 percent of the reductions in CFC use under economic incentives policies are reductions in prompt emissions, implying that a reduction in use during a given year will result in a nearly equal reduction in emissions in the same year.

Third, incentives policies can appropriately concentrate on CFC purchases because the environmental damages associated with CFC emissions are not localized. An individual in any locality benefits equally from a given amount of emissions reduction, regardless of where the reduction occurs. As a result, the geographic distribution of emissions sources is immaterial to an assessment of the environmental improvement resulting from a policy action. This characteristic makes an economic incentive approach far less complicated in CFC regulation than it might be in other regulatory contexts.

## THE BASES OF POLICY COMPARISON

Mandatory controls are targeted at particular activities in individual industries. In contrast, economic incentives policies operate simultaneously on the total market for all regulated CFCs. Consequently, the two policy strategies affect the use of CFCs differently and result in different time profiles of emissions reductions and compliance costs. In this study, we establish a common basis of policy comparison by weighting the CFCs according to their potential for ozone destruction and by measuring cumulative emissions reductions and cumulative compliance costs for the entire period 1980 through 1990.

### Permit Pounds

Models of atmospheric chemistry indicate that the ozone depletion potential of a pound of emissions differs among the various CFC chemicals. A major reason for the differences in the ozone depletion potential of the fully halogenated CFCs is differences in their chlorine content. For example, the chlorine content of a pound of CFC-11 is about one-third greater than that of a pound of CFC-113; a pound of CFC-11 emissions is thus about one-third more hazardous to the ozone layer than a pound of CFC-113 emissions.[3]

To account for these differences, we define a standard unit of measure for CFCs, the permit pound. Each permit pound contains the same amount of chlorine but differing amounts of alternative CFCs. Table 4.1 shows the amount of chlorine contained in the types of CFC considered for regulation in this analysis, along with the conversion factors for translating CFC pounds into permit pounds.[4] These conversion factors use CFC-113 as the base unit of measure, i.e., one pound of CFC-113 is equivalent to one permit pound. Any other of the CFCs could be used as the basis of measurement without affecting the results of the analysis. Measuring emissions in permit pounds allows us to make more accurate comparisons of the environmental improvement under alternative policies.

Throughout this analysis of economic incentives, the price increases generated by taxes or permit quotas are specified as price increments per permit pound, which means that the price increment differs among the CFCs. Suppose, for example, that the tax rate or permit price is 10 cents per permit pound. The corresponding increases in price to CFC users are 13.6 cents per pound of CFC-11, 10.3 cents per pound of CFC-12, 10 cents per pound of CFC-113, and only 2.6 cents per pound of CFC-502. More generally, the CFC price increment can be calculated by multiplying the permit price or tax rate by the appropriate conversion factor from Table 4.1.

Specifying the price increments in terms of permit pounds yields a desirable policy outcome: A single permit price or tax rate automatically yields a higher CFC price increment for the most hazardous CFCs. Thus, the incentives for emissions reductions are greatest where they will do the most good.

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[3] Other chemical properties also affect the relative ozone hazard posed by different CFCs, but chlorine content is a major factor for the fully halogenated CFCs. For further discussion of the importance of chlorine content, see Sec. II. For a discussion of the possibility of devising economic incentives based on other weighting schemes, see Sec. V.

[4] The inverse of each conversion factor in Table 4.2 equals the number of CFC pounds contained in one permit pound. Thus, one permit pound is equivalent to 0.73 pound of CFC-11, 0.97 pound of CFC-12; 1.00 pound of CFC-113; or 3.85 pounds of CFC-502.

Table 4.1

PERMIT POUND CONVERSION FACTORS[a]

| Type of CFC | Chlorine Content per Pound of CFC (pounds) | Conversion Factor (permit pounds per pound of CFC) |
|---|---|---|
| CFC-11 | 0.774 | 1.36 |
| CFC-12 | 0.586 | 1.03 |
| CFC-113 | 0.568 | 1.00 |
| CFC-502[b] | 0.147 | 0.26 |

[a] Calculations explained in text.

[b] CFC-22 comprises 48.8 percent of CFC-502 by weight. The CFC-22 contained in CFC-502 is assumed to be one-tenth as hazardous to the ozone as a comparable amount of CFC-12 (personal communication with Dr. M. J. Molina).

## Cumulative Emissions

Although the data presented here often illustrate policy effects by reporting annual emissions reductions for 1980 and 1990, we are basically concerned with the cumulative emissions effects of policy—the sum of annual emissions reductions occurring from 1980 through 1990. Information supplied by EPA indicates that for a given level of cumulative emissions, the ultimate effects on the ozone layer are not significantly affected by the timing of emissions over a period as short as one decade.[5] Consequently, alternative regulatory strategies can be considered equally effective if they reduce cumulative permit pounds of emissions by the same amount.

## Compliance Costs

The cost comparisons, although based on annual compliance costs, are specified in terms of the present value of compliance costs over the entire period 1980 through 1990. The present value of cumulative compliance costs is a useful summary measure when different policies yield different time profiles of costs. The discounting of future costs in computing the present value reflects the fact that firms can earn a return on invested capital. If compliance costs are not incurred until a future year, a firm can invest in a profitable activity and be earning a return on the investment that will help pay the future compliance costs. Thus, compliance costs in the future are less "expensive" per dollar than are those incurred today.[6]

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[5] The timing of the ultimate effect might vary as the time profile of emissions varies, but not enough to influence our policy comparisons. (See Sec. II.)

[6] An 11 percent discount rate was used in computing the present values in this study. This rate was chosen for consistency with other EPA-sponsored research on the benefits of ozone protection, and it approximately measures the current real rate of return on nonconstruction investment. (See Sec. II.)

The time profile of compliance costs under mandatory controls is determined by the nature of the controls and by industry growth rates under those controls. The profile can be varied only by changing the implementation date, and that would cause the cumulative emissions reduction to vary as well. In contrast, the time profile of costs under economic incentives can be varied while holding the cumulative emissions reduction constant. It is possible to take advantage of this feature of economic incentives, both in easing the transition to regulation and, as explained below, in lowering discounted cumulative compliance costs.

## THE MANDATORY CONTROL BENCHMARK

The emissions effects and compliance costs of economic incentives policies are compared here with the outcomes of the "benchmark" mandatory controls identified in Secs. III.A through III.H. These comparisons include all the potentially enforceable options that have measurable effects during the period of study and for which adequate data on costs are available. These options are:

1. Recovery and recycling of CFC-11 in slabstock and molded flexible foam plants.
2. Setting equipment standards for users of CFC-113 in cleaning and drying applications.
3. Recovery and recycling of CFC-12 in thermoformed extruded polystyrene sheet plants.
4. Conversion to R-22 test gas in the manufacture of chillers.
5. Conversion to R-22 test gas in the manufacture of retail food refrigeration systems.
6. Conversion to R-502 refrigerant in medium temperature (nonfreezing) retail food refrigeration systems.

For reference purposes, Table 4.2 summarizes the emissions reductions and compliance costs under the benchmark mandatory controls, as estimated in Secs. III.A through III.H. Assuming perfect compliance, the combined set of mandatory controls would achieve a reduction in cumulative emissions of 812 million permit pounds, generating $185.3 million in discounted cumulative compliance costs.

## ESTIMATING EMISSIONS AND COSTS UNDER ECONOMIC INCENTIVES POLICIES

Under economic incentives policies, the extent of emissions reduction and the level of compliance cost are determined by the demand for CFCs in each product area as estimated in the preceding sections of this report. To estimate the product area demand schedules, we calculated "critical prices" at which certain technical options would become cost-effective for various groups of users. When the product

Table 4.2

ESTIMATED EFFECTS OF THE BENCHMARK MANDATORY CONTROLS

| Product Area | CFC | Annual Reductions in Emissions (millions of pounds) | | 1980-1990 Cumulative Emissions Reduction (millions) | | 1980-1990 Cumulative Compliance Costs[b] (millions of dollars) |
|---|---|---|---|---|---|---|
| | | 1980 | 1990 | CFC Pounds | Permit Pounds[a] | |
| Flexible foams | CFC-11 | 26.5 | 40.5 | 368.5 | 501.2 | 93.3 |
| Solvents | CFC-113 | 10.0 | 32.5 | 185.7 | 185.7 | 45.7 |
| Rigid foams | CFC-12 | 7.2 | 11.3 | 103.0 | 106.1 | 38.8 |
| Retail food refrigeration | CFC-12 | 1.0 | 4.0 | 22.9 | 18.3 | 7.3 |
| | CFC-502[c] | -0.7 | -3.9 | -20.4 | | |
| Chillers | CFC-12 | 0.1 | 0.1 | 1.0 | 1.0 | 0.1 |
| Total[d] | Non-CFC-22 | 44.1 | 84.6 | 660.7 | 812.3 | 185.3 |

SOURCE: Detailed calculations presented in Secs. III.A. through III.G. Components may not sum to totals because of rounding.

[a] One permit pound is equivalent to 1.00 pound of CFC-113, 0.97 pounds of CFC-12, 0.73 pounds of CFC-11, and 3.85 pounds of CFC-502.

[b] The cumulative compliance costs are the sums of annual compliance costs in constant 1976 dollars discounted at 11 percent per year.

[c] The negative signs for CFC-502 emissions reductions indicate that those emissions would increase under the mandatory control.

[d] The totals for non-CFC-22 exclude the 48.8 percent of CFC-502 that is comprised of CFC-22.

area demand schedules are translated into permit pounds and summed, the result is the aggregate demand schedule used to specify the outcomes of tax or permit quota policies. By subtracting the amount the CFC producers charge from each demand price, we obtain a demand schedule that shows the quantity of use that would result from various price increments that might be set by policy.

As an illustration, Table 4.3 shows selected points on the aggregate demand schedules for 1980 and 1990.[7] The table also identifies the product areas that would be undertaking emissions-reducing activities at each of the indicated tax rates or permit prices. Because of the cautious assumptions employed to estimate critical prices in Secs. III.A through III.H, the price increments shown in the table tend to be higher than necessary to induce the indicated reductions in CFC use.[8] In particular, we do not estimate reductions in use from technical options for which cost data are inadequate to estimate critical prices. Moreover, the estimates do not include prospective reductions in use resulting from technological innovations that might be induced by higher CFC prices.

In the absence of regulatory action to increase CFC prices, total CFC use is projected to be 455 million permit pounds in 1980, rising to 784 million in 1990, for a cumulative total of 6,669 million. However, as Table 4.3 illustrates, higher CFC prices would result in lower CFC use levels. For example, an economic incentives policy that increases prices by as little as 35 cents per permit pound would induce

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[7] Appendix C contains more detailed tables of the market demand schedules for CFC-11, CFC-12, and CFC-113 and for the aggregate demand schedule used to specify outcomes under economic incentives.

[8] Sections III and III.A through III.H indicate the nature of the uncertainties surrounding the estimates of critical prices.

## Table 4.3

### AGGREGATE DEMAND SCHEDULES FOR CFCs, 1980 AND 1990

| Price Increment[a] (dollars per permit pound) | Product Areas of Induced Activities[b] | Quantity of CFC Demanded[c] (millions of permit pounds) | |
|---|---|---|---|
| | | 1980 | 1990 |
| 0.00 | — | 455 | 784 |
| 0.23 | FF, SOL, RFR, PS | 422 | 718 |
| 0.35 | FF, SOL | 401 | 706 |
| 0.51 | FF, SOL | 396 | 676 |
| 0.87 | FF, SOL, PS | 368 | 632 |
| 1.19 | PS | 364 | 626 |
| 1.54 | SOL, PS, MAC | 348 | 598 |
| 2.03 | SOL | 344 | 598 |
| 2.20 | SOL | 344 | 590 |

SOURCE: Based on detailed calculations presented in Secs. III.A. through III.H. Data shown only for selected price increments. See Appendix C for detailed tables of all demand points calculated in this analysis.

[a] Price increment in constant 1976 dollars above CFC supply prices. For CFC-113, the supply price declines as production increases, as a result of economies of scale.

[b] FF = flexible foams, SOL = solvents, PS = polystyrene sheet, RFR = retail food refrigeration, MAC = mobile air conditioning.

[c] Includes demand for CFC-11, CFC-12, CFC-113, and CFC-502 in retail food refrigeration. One permit pound is equivalent to 1.00 pounds of CFC-113, 0.97 pounds of CFC-12, 0.73 pounds of CFC-11, and 3.85 pounds of CFC-502.

emissions reductions in virtually every product area where options for reducing emissions are available.

Table 4.4 translates the effects of selected CFC price increments into annual emissions effects and shows the annual compliance costs required for successively larger emissions reductions.[9] The table also predicts the cumulative emissions reductions and compliance costs that would result from each cited price increment if it were established in 1980 and maintained through 1990. In so doing, the table illustrates two important features of economic incentives policies.

First, incentives can achieve a much wider range of emissions reductions than simply those equivalent to the benchmark mandatory controls. At a price increment of just seven cents, the incentives policy could reduce emissions by 326 million permit pounds, less than half of the benchmark reduction, while at a price increment of $2.20, incentives can reduce cumulative emissions by 1,602 million pounds, almost twice as much as the benchmark.

Second, the table shows that in order to increase reductions in emissions, compliance costs must rise far more than proportionately. The compliance cost for

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[9] The price increments in Table 4.4 can be interpreted as the marginal costs of avoiding emissions.

## Table 4.4

### EMISSIONS REDUCTIONS AND COMPLIANCE COSTS AT SELECTED PRICE INCREMENTS[a]

| Price Increment ($ per permit pound) | 1980 |  | 1990 |  | Cumulative 1980-1990[b] |  |
|---|---|---|---|---|---|---|
|  | Emissions Reduction (millions of permit pounds) | Compliance Costs (millions of $) | Emissions Reduction (millions of permit pounds) | Compliance Costs (millions of $) | Emissions Reduction (millions of permit pounds) | Compliance Costs[c] (millions of $) |
| 0.07 | 23.2 | 1.5 | 37.0 | 2.4 | 326 | 12.6 |
| 0.20 | 26.6 | 2.7 | 59.6 | 6.7 | 454 | 27.8 |
| 0.35 | 50.1 | 9.9 | 74.6 | 10.5 | 680 | 69.8 |
| 0.51 | 55.1 | 12.4 | 105.0 | 25.8 | 856 | 117.3 |
| 0.85 | 75.8 | 26.5 | 137.5 | 50.2 | 1144 | 240.1 |
| 1.19 | 86.9 | 37.0 | 154.4 | 66.2 | 1296 | 326.5 |
| 1.54 | 103.2 | 58.5 | 182.5 | 105.8 | 1535 | 518.8 |
| 2.20 | 107.8 | 67.8 | 190.3 | 121.9 | 1602 | 599.7 |

SOURCE: Calculations based on data in Appendix C.

[a] All costs and prices measured in constant 1976 dollars.

[b] Assumes indicated price increment is constant in real terms from 1980 through 1990 and that the CFC demand schedule shifts horizontally over time at a constant rate.

[c] Present value of 1980 through 1990 annual compliance costs, discounted at 11 percent.

the first 326 million permit pounds of emissions reduction (achieved when the price increment is just seven cents) is less than $13 million. In contrast, raising the price increment from $1.54 to $2.20 increases cumulative emissions reductions by merely 67 million permit pounds—but adds $81 million to cumulative compliance costs.

## OUTCOMES UNDER FOUR INCENTIVE POLICY DESIGNS

Compliance costs under economic incentives are analyzed for three emissions-reduction scenarios. The first scenario, called the "benchmark equivalent," achieves about the same cumulative emissions reduction as the benchmark mandatory controls. The second scenario, called "low growth," minimizes the average annual rate of growth in CFC use subject to a maximum 1990 price increment of $2.20; this scenario yields cumulative emissions reductions only slightly greater than the benchmark-equivalent scenario, but is useful for illustrating the cost implications of targeting policy on CFC growth rates rather than on cumulative emissions. The third, or "zero-growth," scenario reduces cumulative emissions by an amount approximately equivalent to holding annual CFC use constant at 1980 levels throughout the next decade.[10]

There are several time profiles of annual emissions reductions that yield the same cumulative reduction in emissions. Under economic incentives, different time profiles are obtained by varying the annual tax or permit price during the decade. Within the benchmark-equivalent scenario, two incentive policy designs are considered here, one that imposes a tax or permit price that is constant (in real terms) throughout the period, and one that minimizes cumulative compliance costs by starting with a smaller 1980 price increment but raising it each year. By definition, the low-growth scenario requires rising tax rates or permit prices over the period in order to limit the growth rate for CFC use. For the zero-growth scenario, only the constant-price-increment design is reported, because our cautious assumptions about CFC demand imply that a very high tax or permit price would have to be set throughout the entire period to achieve a cumulative emissions reduction equivalent to zero growth. Hence there are four incentive policy designs, two for the benchmark-equivalent scenario and one each for low and zero growth. As elsewhere in this report, all price and compliance cost data are specified in constant 1976 dollars.

### Benchmark-Equivalent Policy Designs

Table 4.4 indicated that the benchmark cumulative emissions reduction of 812 million permit pounds could be achieved by a constant price increment between 35 and 51 cents per permit pound. By interpolation, the point estimate of the price increment required for the benchmark-equivalent scenario is 50 cents.[11] This would be the constant tax rate under a tax policy, or alternatively, the permit price under a quota policy that sets a quota of 396 million permit pounds in 1980 and raises the quota by about 5.6 percent per year.

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[10] The period considered in this analysis, 1980 through 1990, actually amounts to 11 years, but we refer to it as a decade for expositional convenience.

[11] According to the aggregate demand schedule, economic incentives would achieve the same cumulative emissions reduction as the benchmark controls when the price increment is between 49 and 50 cents. We use 50 cents for the constant-price case, thereby obtaining slightly larger emissions reductions than under the benchmark controls.

Table 4.5 presents estimates of the product area outcomes under the constant-price, benchmark-equivalent policy. An example illustrates how the product area outcomes are estimated from the product area demand schedules of the preceding sections, and also how one of the cautious assumptions in our analysis influences the estimates of aggregate and product area outcomes:

*Example:*

In flexible foams, which use CFC-11, a tax or permit price of 50 cents corresponds to an increase in the CFC price of 68 cents per pound. When added to the current price of CFC-11 (34 cents in 1976 dollars), the policy price increment raises the CFC-11 price to $1.02. This lies between the price (68 cents) at which certain small producers of slabstock foams find methylene chloride conversion cost-effective and the price ($1.04) at which small producers of molded foams find recovery and recycle cost-effective. According to the product area demand curve, a price of 68 cents per pound of CFC-11 would reduce 1980 CFC use (and emissions) to 27 million pounds, and would reduce 1990 use (and emissions) to 41 million pounds. Relative to the baseline use and emissions projections, a price of 68 cents reduces cumulative use and emissions by about 25 percent, which amounts to 381 million permit pounds as indicated in Table 4.5. Note, however, that if tax rate or permit price rose by just one cent (to 51 cents per permit pound), the price of CFC-11 would become $1.04 per pound and the small molded foamers would contribute another 51 million permit pounds to the emissions reduction in this product area.[12] Though some molded foamers might begin recovery and recycle at prices slightly below $1.04 for CFC-11, our cautious assumption is that they would not begin this activity unless the tax rate or permit price reaches 51 cents.

Overall, this benchmark-equivalent policy design generates cumulative compliance costs of $108 million, only 58 percent as high as the costs for the benchmark mandatory controls. The substantial resource savings that result from using economic incentives are the result of a reallocation of emissions reduction activities. Under an incentives policy, emissions-reduction activities whose unit cost is greater than the price increment per permit pound are not undertaken. Hence, some relatively high-cost activities that are required to achieve the benchmark emissions reduction under mandatory controls are not undertaken under economic incentives. For example, at a price increment of 50 cents, smaller extruded polystyrene sheet plants do not find CFC recovery economical, so the policy results in less emissions reductions in the rigid foam product area than would occur under mandatory controls. The economic incentives policy design compensates for this by encouraging larger emissions reductions in solvents, where an alternative chemical can be substituted for the CFCs at unit resource costs of less than 50 cents per permit pound. There are also cost saving redistributions of activities within product areas; for example, while many flexible foam producers do less to reduce emissions under incentives, some large producers of flexible slabstock foam increase their emissions reductions by 50 percent.

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[12] The conversion factors shown in Table 4.1 are rounded. In calculations, we use 1.3644 for the CFC-11 conversion factor. Hence, a permit price of 51 cents raises the CFC price to $1.04 (rather than $1.03).

## Table 4.5

### CONSTANT-PRICE-INCREMENT DESIGN VERSUS MANDATORY CONTROLS: COMPLIANCE COSTS FOR SIMILAR EMISSIONS REDUCTIONS

| | Cumulative Effects of Economic Incentives[a] | | Deviation from Mandatory Controls | |
|---|---|---|---|---|
| Product Area | Emissions Reduction (millions of permit pounds) | Compliance Cost[b] | Emissions Reduction (millions of permit pounds) | Compliance Cost[b] |
| Flexible foam | 380.7 | 29.2 | -120.5 | -64.1 |
| Solvents | 390.3 | 67.3 | +204.6 | +21.6 |
| Rigid foam | 26.7 | 3.8 | -79.4 | -35.0 |
| Retail food | 18.3 | 7.3 | -- | -- |
| Chillers | 1.0 | 0.1 | -- | -- |
| Total | 816.9 | 107.8 | +4.6 | -77.5 |

SOURCE: Based on detailed calculations in Secs. III.A through III.H.

[a] Based on constant price increment of $0.50 per permit pound (1976 dollars).

[b] Present value of annual compliance costs in millions of 1976 dollars, discounted at 11 percent.

The constant-price benchmark-equivalent design generates a time-path of annual emissions quite similar to that of the mandatory controls, with substantial reductions below baseline in the initial year of the policy and growth thereafter that parallels the baseline growth curve.[13] Alternatively, the same cumulative emissions reduction would be achieved by setting a lower initial price increment but raising it gradually over time. Correspondingly, the initial emissions reduction would be less than under a constant-price design, but the reductions in later years would be greater. Increasing-price policy designs therefore ease industry's transition to regulation.

A particularly interesting form of an increasing-price policy is one that raises the tax rate or permit price at the same rate as industry's discount rate for investment—11 percent in this study. If the price increment rises at this rate throughout the period, the policy minimizes the present value of compliance costs.[14] Table 4.6 describes a marketable permit policy design that minimizes the present value of compliance costs while achieving the benchmark emissions reduction. The annual quotas shown would yield the predicted annual permit prices shown. Equivalently, the policy design could consist of a tax rate of 25 cents per permit pound in 1980 that rises in real terms at 11 percent per year throughout the period.[15]

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[13] The baseline average annual growth rate in CFC use is 5.6 percent.

[14] This necessarily minimizes the present value of compliance costs because it equalizes the discounted marginal cost of emissions-reducing activities across years. As a result, it would be impossible to reduce compliance costs by shifting activities between years. In contrast, under a constant price increment of 50 cents, the discounted cost of activities induced at the margin in 1980 is 50 cents, while the discounted cost of the marginal activity in 1990 is only 18 cents. Consequently, shifting one pound of emissions reduction from 1980 to 1990 would result in a saving of 32 cents.

The cumulative emissions effects and compliance costs of the cost-minimizing design are summarized in Table 4.7 and compared with the mandatory control and constant-price policy designs that achieve similar environmental improvement over the decade. As expected, the present value of compliance costs under the cost-minimizing design, $95 million, is less than that under the alternative policies. In fact, the cost-minimizing design is only half as costly as the benchmark mandatory controls. However, the savings relative to a constant price increment of 50 cents per permit pound are not large, because of the tradeoff between the timing of emissions-reduction activities and the increasing costs of those activities. The postponement of emissions reductions is beneficial in one sense, since the capital that would otherwise be engaged in these activities is available to generate income in other pursuits (presumably with a rate of return equal to the opportunity cost of capital). However, if the same cumulative emissions goal is to be achieved, more costly activities must be induced during later years,[16] and the net result is only a modest savings in discounted compliance costs.

## Low-Growth and Zero-Growth Policy Designs

Economic incentives policies can be designed to ease the transition to regulation even more than under the cost-minimizing approach. However, this requires a rapid rate of increase in the tax rate or permit price and causes much higher compliance costs than other policy designs that yield about the same cumulative reductions in emissions. These implications are well illustrated by the low-growth scenario.

By setting the price increment near zero (specifically, seven cents per permit pound) in 1980 and allowing it to reach the upper bound in our models ($2.20) in 1990, we can define a low-growth scenario for use and emissions. This low-growth policy reduces cumulative emissions by 869 million permit pounds and results in discounted compliance costs of about $143 million. The low-growth design is only slightly more effective than the benchmark-equivalent incentives policies, but is 32 to 51 percent more costly. Relative to mandatory controls, however, the low-growth policy substantially delays industry action, is slightly more effective at reducing cumulative emissions, and also reduces cumulative compliance costs by 23 percent.

Economic incentives might achieve even greater emissions reductions than those indicated in Tables 4.7 and 4.8, because our analysis of the emissions effects and compliance costs of all the economic incentives policies is designed to be extremely cautious. In particular, many of the CFC applications are assumed to be unresponsive to CFC prices even though we anticipate that higher prices within the

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[15] If a different discount rate were used to calculate the present value of compliance costs, the cost-minimizing policy would involve a price increment that rises at the new discount rate rather than 11 percent.

[16] In effect, the cost-minimizing policy design "moves up" the CFC demand schedule during later years. For example, the higher price increments in Table 4.6 will eventually induce some use of CFC recovery in smaller foam plants and greater amounts of chemical substitution by CFC-113 solvent users—activities that are not generated by a constant price increment of 50 cents.

## Table 4.6

### ANNUAL QUOTAS AND PERMIT PRICES UNDER A COST-MINIMIZING, BENCHMARK-EQUIVALENT DESIGN, 1980 TO 1990

| Year | Permit Quota (millions of permit pounds) | Estimated Permit Price (1976 $) | Emissions Reduction (millions of permit pounds) |
|---|---|---|---|
| 1980 | 414.7 | 0.25 | 36.6 |
| 1981 | 433.6 | 0.28 | 43.2 |
| 1982 | 454.1 | 0.31 | 49.6 |
| 1983 | 476.5 | 0.34 | 55.6 |
| 1984 | 501.1 | 0.38 | 61.0 |
| 1985 | 526.8 | 0.42 | 66.9 |
| 1986 | 552.5 | 0.47 | 74.7 |
| 1987 | 574.7 | 0.52 | 87.8 |
| 1988 | 598.6 | 0.58 | 101.2 |
| 1989 | 629.3 | 0.64 | 109.9 |
| 1990 | 661.1 | 0.71 | 119.7 |
| Cumulative | 5,823.0 | -- | 806.1 |

SOURCE: Calculations based on Tables 4.4 and 4.5 and Secs. III.A through III.H. It is assumed that the demand schedule for permits shifts horizontally over time at a constant rate of growth. For some interim years, estimates are based on linear interpolation of demand schedules.

## Table 4.7

### COMPARISON OF ALTERNATIVE POLICIES HAVING SIMILAR CUMULATIVE EMISSIONS REDUCTIONS

| Policy Design | Emissions Reduction (millions of permit pounds) | | | Total Compliance Costs (millions of 1976 $) | | |
|---|---|---|---|---|---|---|
| | 1980 | 1990 | Cumulative 1980-1990 | 1980 | 1990 | Cumulative 1980-1990[a] |
| Mandatory controls | 54.4 | 102.5 | 812.3 | 20.9 | 37.0 | 185.3 |
| Economic incentives | | | | | | |
| Constant price design[b] | 54.8 | 96.9 | 816.9 | 12.3 | 21.8 | 107.8 |
| Cost minimizing design[c] | 36.6 | 119.4 | 806.1 | 5.2 | 35.0 | 94.7 |

SOURCES: Calculations based on Tables 4.2, 4.3, and 4.6, and Secs. III.A through III.H.

[a] Present value of annual compliance costs, discounted at 11 percent.

[b] Based on linear interpolation of annual demand schedules for permit pounds with a constant tax rate or permit price of $0.50 from 1980 through 1990.

[c] Based on linear interpolation of annual demand schedules for permit pounds with tax rate or permit price rising from $0.25 in 1980 to $0.71 in 1990.

### Table 4.8

### EFFECTS OF LOW-GROWTH AND ZERO-GROWTH POLICY DESIGNS

| Emissions Reduction (millions of permit pounds) | | | Compliance Costs (millions of 1976 $) | | |
|---|---|---|---|---|---|
| 1980 | 1990 | Cumulative 1980-1990 | 1980 | 1990 | Cumulative 1980-1990[a] |
| Low-Growth Design[b] | | | | | |
| 6.0 | 190.0 | 868.5 | 0.3 | 121.9 | 142.8 |
| Zero-Growth Design[c]<br>Cautious Assumptions | | | | | |
| 107.8 | 190.0 | 1,601.9 | 67.8 | 121.9 | 599.9 |
| Zero-Growth Design[d]<br>Alternative Assumptions | | | | | |
| 107.9 | 194.8 | 1,625.3 | 30.8 | 53.6 | 268.2 |

SOURCE: Calculations based on tables in Appendix C.

[a] Present value of 1980 through 1990 annual compliance costs, discounted at 11 percent.

[b] Assumes price increment of $0.07 per permit pound in 1980, rising at constant rate to $2.20 in 1990.

[c] Assumes price increment is $2.03 per permit pound in 1980, rising to $2.20 in 1990.

[d] Assumes constant price increment of 64 cents per permit pound.

range under consideration will actually cause significant reductions in CFC use and emissions.[17]

Baseline projections of the CFC market imply that in the absence of regulation, cumulative CFC use from 1980 through 1990 will be about 6.7 billion permit pounds. Based on available data, we can predict the price-responsiveness of demand for 80 percent of this CFC use, including 3.2 billion permit pounds (primarily in foam insulation and refrigeration products) that are not expected to respond to higher CFC prices in the relevant range, as well as about 2.1 billion permit pounds in product areas where responses to CFC prices have been estimated.

The remaining 20 percent of the baseline cumulative use, about 1,325 million permit pounds, occurs in applications for which available information is inadequate to predict the prices at which emissions reductions might occur. For these applications, which include some uses in the solvents, rigid foams, mobile air conditioning, LFF, sterilants, and other "miscellaneous" applications, the foregoing analysis uniformly adopts the assumption that CFC demand is perfectly inelastic.

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[17] We have also ignored technological developments induced by higher CFC prices. If economic incentives strategies induce CFC-saving innovations (as can be expected), actual emissions reductions will be greater than those predicted by our analysis, which is necessarily predicated on the existing state of technology.

If we maintain the inelasticity assumption with respect to these applications, a zero rate of growth in CFC use beyond 1980 is not achievable without exceeding a price increment of $2.20 and thereby violating the conditions assumed in the product area demand analysis. (See Sec. II.) Given our cautious assumptions, the cumulative emissions reduction that would result from preventing CFC market growth can almost be achieved, however, if a price increment greater than $2.00 is established in 1980 and maintained through 1990.[18] This policy design would reduce cumulative emissions by 1.6 billion permit pounds (about 99 percent of the effectiveness of preventing growth in use) at cumulative compliance costs of almost $600 million.

However, there are three reasons to suspect that the inelasticity assumption is overly cautious, particularly for predicting the emissions effects of large price increments. First, in several of the applications where CFC demand is inelastic by assumption (e.g., LFF, sterilants, mobile air conditioning), options for reducing emissions have been identified but are not reflected in the CFC demand schedules solely because of the lack of cost data. Second, in certain applications (e.g., packaging applications of rigid urethane and some nonurethane foams) there appear to be final product substitutes that do not use CFCs, but the prices at which substitution would occur are unknown. Finally, for several small and highly specialized applications, little or no information is available on options for reducing emissions, but there is no evidence to suggest that emissions-reducing activities would fail to occur under economic incentives.

Although the response of these product areas to economic incentives obviously cannot be predicted precisely with available information, these applications well might contribute to emissions reductions under an economic incentive policy, especially one as stringent as the zero-growth scenario. If the demand elasticity in these applications proves to be as great as in the product areas where our analysis now predicts price responsiveness, then a constant price increment of just 64 cents (by interpolation) would actually generate about 1.7 billion permit pounds of emissions reduction—equivalent to the reduction that would be achieved by a policy that freezes annual CFC use at the 1980 level of 454 million permit pounds. Based on the same seemingly reasonable assumption of equal elasticities, an economic incentive policy design that increases CFC prices by more than 64 cents per permit pound would actually reduce cumulative emissions below the zero-growth level.

In contrast, given current technology a mandatory control policy appears incapable of achieving comparable emissions reductions. The benchmark mandatory controls produce less than half the cumulative emissions reduction available from a zero-growth policy. Even if we added in the mandatory control options that appear enforceable but that were excluded from the benchmark because their compliance costs could not be determined from available data, the entire set of enforceable controls would produce only about 60 percent of the emissions reduction of zero growth.[19] Table 4.8 reports predicted outcomes for the low-growth policy design as well as for the zero-growth designs under both the cautious and alternative assumptions.

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[18] In 1990, $2.20 is the highest price increment measured on our demand curves. However, in 1980, the highest price increment is $2.03. Thus, the emissions effect of a policy that starts at $2.03 in 1980 and reaches $2.20 in 1990 is the same as one that maintains $2.20 throughout the period. Because the latter design unnecessarily raises the estimates of cumulative compliance costs and transfer payments, we assume that the zero-growth policy instead begins in 1980 with a price increment of $2.03.

## SUMMARY

On the basis of costs to the economy as a whole, the case in favor of economic incentives policy designs is indeed persuasive. Relative to mandatory controls, economic incentives can reduce compliance costs by about half, while achieving comparable environmental improvement.

Furthermore, economic incentive policies can produce greater emissions reductions than can mandatory controls, a feature that may become vitally important if CFC destruction of the ozone layer is found to warrant substantial emissions reductions. Unlike currently available mandatory controls, economic incentives appear capable of achieving the cumulative emissions effects of zero, perhaps even negative, growth rates in CFC use without significant sacrifices of the services now provided by products produced with CFCs.

To complete the comparison of economic incentives with mandatory controls, however, we must consider the distributive effects of the alternative policies, along with some important implementation issues. These factors will be addressed in Sec. V.

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[19] The excluded mandatory control candidates and their potential reductions in cumulative emissions are (1) helium leak testing in home appliances, one million pounds of CFC-12; (2) recovery at rework in home appliances, three million pounds of CFC-12; (3) requiring reciprocating compressors in all new home appliances, one million pounds of CFC-12; (4) reducing the average initial charge in mobile air conditioners to 2.75 pounds, 40 million pounds of CFC-12; and (5) recovery and recycle or gas substitution in sterilants, 200 million pounds of CFC-12. Together, adding these controls to the benchmark could increase the benchmark emissions reduction by 252 million permit pounds, but at unknown compliance costs. Other mandatory control candidates would yield the bulk of their emissions effects after 1990.

# V. DISTRIBUTIVE EFFECTS AND OTHER REGULATORY ISSUES

Section IV identified substantial differences between incentives policies and mandatory controls in both potential effectiveness and costs to the economy as a whole. The two policy strategies also differ along a number of other dimensions that are considered in this section.

Aside from the magnitude of resource costs imposed by regulation, an important economic implication of regulatory activity lies in its distribution of costs among firms, industries, and consumers. For economic incentives policies, the distributive consequences depend critically on how the policy is implemented. The first portion of this section examines the distribution of costs under alternative policies and implementation approaches.

Because the operational features of mandatory control programs are familiar, little needs to be said about them here. However, the operational features of economic incentives for environmental regulation are novel and deserve some discussion in the remainder of this section.

## DISTRIBUTION OF COSTS

Under mandatory controls, the only costs imposed on the CFC-using industries (aside from administrative costs) are compliance costs, the costs of resources used to limit CFC emissions. All of these costs are initially paid by the regulated firms, but our analysis suggests that most—if not all—of these costs will ultimately be paid by final product consumers in the form of higher prices for the products made by the CFC-using industries. Because technical options to limit CFC emissions would contribute a relatively small sum to total production costs in the industries that would be subject to mandatory controls, the final product price increases attributable to regulation should be modest, amounting to less than five percent in any industry.

The cost and price increases will not be uniform across CFC-using industries under mandatory controls. Some of the industries would not be subject to any regulation under the benchmark set of mandatory controls, and would therefore face no increase in costs or prices. Data in Sec. IV showed that the industries subject to regulation would face differing costs. The distribution of mandatory control costs is reviewed below when they are compared with economic incentives costs.

Under economic incentives policies, firms subject to regulation still incur compliance costs for resources they use to limit CFC emissions. Section IV showed that these compliance costs are lower in total than under mandatory controls that would achieve the same emissions reduction. The preceding section also showed that compliance costs are distributed differently under economic incentives, with lower costs for producers of flexible foams and rigid packaging foams and higher costs for users of solvents. As in the case of mandatory controls, we expect virtually all incentives policy compliance costs to be passed through to final product consumers, but the different distribution of compliance costs implies that the price increases under incentives policy will be spread among final products differently than under mandatory controls.

If, under an incentives policy, firms must pay more than the unregulated price for any of the CFCs they continue to use, the added CFC payments—termed transfer payments in Sec. II—impose an added expense on the firms that pay them. In principle, the transfers will ultimately benefit firms or consumers elsewhere in the economy,[1] but the benefits might be so diffusely distributed in our trillion-dollar economy that the recipients would be far harder to identify than the relatively small number of industries (and their customers) that make the payments. Moreover, even if the transfers are paid by some CFC users to others or to the CFC producers, the transfers might be a policy concern because of their readily apparent effects on the distribution of policy expenses among industries.

The magnitude of transfer payments depends on how an economic incentives policy is implemented. As defined in Sec. II, an "uncompensated" incentives policy is one that requires CFC users to pay taxes, buy permits, or pay higher prices for all the CFCs they continue to use under the policy.[2] An uncompensated incentives policy design would generate large transfer payments, ranging from a discounted cumulative total of 1.5 billion dollars for the benchmark-equivalent cost-minimizing design to 6.2 billion dollars for the zero-growth design based on cautious assumptions about the CFC demand curves.[3]

The size of the annual transfers for each product area is estimated by multiplying the amount of continuing CFC use under the policy by the tax or permit price for each incentives policy design. Uncompensated transfer payments by product area under the benchmark-equivalent and low-growth policies are shown in Tables 5.1 and 5.2. For zero growth under the cautious assumptions,[4] uncompensated cumulative transfer payments range from a low of $100 million for rigid packaging foams to a high of $2,370 million for rigid insulating (and other rigid) foams; the transfers for flexible foams would be $213 million, and the transfers for solvents would be $740 million. However, these estimates reflect the extreme assumption that many applications would not contribute to emissions reductions even if the price increment were over $2.00 per permit pound. Under alternative and more plausible assumptions about price responsiveness in these applications,[5] estimated transfer payments are much lower overall, perhaps as low as $1.6 billion.[6] Of course, without more data about CFC demand schedules in these applications, we cannot predict the precise magnitude of transfer payments per application.

Under mandatory controls, the total expense imposed on regulated industries

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[1] If there are lags or transition costs associated with transfer payments, there would be some cost imposed on the economy as a whole as a result of transfer payments. However, these effects should be small and difficult to pinpoint.

[2] Our estimates of transfer payments assume that only CFC-11, CFC-12, CFC-113, and CFC-502 are regulated.

[3] See the discussion of the zero-growth scenario, Sec. IV.

[4] Recall from Sec. IV that the cautious analysis assumes that there would be no response to higher prices in applications where data on technical options are incomplete.

[5] Under the alternative assumptions, applications with incomplete data on technical options are on average just as responsive to CFC prices as applications for which data on technical options are more complete.

[6] Under the alternative assumptions transfer payments are lower because the price increment required for zero growth declines to 64 cents.

## Table 5.1

## UNCOMPENSATED TRANSFER PAYMENTS UNDER ECONOMIC INCENTIVES ACHIEVING THE BENCHMARK EMISSIONS-REDUCTION LEVEL

(Millions of 1976 dollars)

| Product Area | Constant-Price Design[a] | | | Cost-Minimizing Design[b] | | |
|---|---|---|---|---|---|---|
| | 1980 | 1990 | Cumulative 1980-1990[c] | 1980 | 1990 | Cumulative 1980-1990[c] |
| Flexible foam | 18.3 | 28.1 | 158.7 | 9.2 | 32.9 | 115.2 |
| Solvents | 27.0 | 48.9 | 239.6 | 17.9 | 64.6 | 224.6 |
| Rigid foam: | | | | | | |
| Insulation and other | 57.3 | 126.8 | 558.3 | 28.7 | 180.1 | 488.5 |
| Packaging | 9.3 | 14.9 | 78.1 | 4.7 | 17.0 | 58.3 |
| Mobile air conditioning | 50.9 | 64.4 | 386.2 | 25.5 | 91.5 | 317.9 |
| Chillers | 9.3 | 13.2 | 74.2 | 4.6 | 18.8 | 61.2 |
| Home refrigeration | 3.7 | 4.8 | 28.3 | 1.8 | 6.9 | 23.3 |
| Retail food | 4.8 | 3.6 | 29.6 | 2.4 | 5.1 | 23.2 |
| Miscellaneous | 17.7 | 36.8 | 167.5 | 8.9 | 52.3 | 145.8 |
| Total | 198.3 | 341.8 | 1,720.5 | 103.7 | 469.4 | 1,458.3 |

SOURCE: Based on detailed calculations presented in Secs. III.A through III.H and IV. Components may not sum to totals because of rounding.

[a] Based on constant-price increment of $0.50 per permit pound.

[b] Based on price increments of $0.25 per permit pound in 1980 and $0.71 in 1990.

[c] Present value of transfer payments from 1980 to 1990, discounted at 11 percent.

Table 5.2

UNCOMPENSATED TRANSFER PAYMENTS UNDER LOW-GROWTH POLICY
(Millions of 1976 dollars)

| Product Area | Low-Growth Design[a] | | |
|---|---|---|---|
| | 1980 | 1990 | Cumulative 1980-1990[b] |
| Flexible foam | 3.2 | 41.1 | 85.7 |
| Solvents | 3.6 | 149.2 | 219.5 |
| Rigid foam: | | | |
| Insulation and other | 5.7 | 558.1 | 667.0 |
| Packaging | 1.0 | 20.5 | 37.7 |
| Mobile air conditioning | 5.1 | 272.8 | 373.8 |
| Chillers | 0.9 | 58.3 | 77.2 |
| Home refrigeration | 0.4 | 21.3 | 29.1 |
| Retail food | 0.7 | 15.4 | 27.4 |
| Miscellaneous | 1.8 | 162.2 | 197.2 |
| Total | 22.4 | 1,299.1 | 1,714.6 |

SOURCE: Results approximate, based on dated for 1980 and 1990 from Secs. III.A through IV. Components may not sum to totals because of rounding.

[a] Based on price increment of $0.05 in 1980 and $2.20 in 1990.

[b] Present value of annual transfer payments from 1980 to 1990, discounted at 11 percent.

(and their customers) is simply the total compliance cost for the policy. Under incentives policy, the total expense imposed on regulated firms is the sum of compliance costs and transfer payments. Figure 5.1 illustrates the comparison of total industry costs between mandatory controls and uncompensated economic incentives for the constant-price, benchmark-equivalent design.

In Figure 5.1, compliance costs are shown by the solid bars for mandatory controls and by the "open" portions of the bars for economic incentives. There are some product areas (e.g., rigid insulating foams) that do not appear to have technical options for reducing emissions, and there are some product areas (e.g., liquid fast freezing and sterilants) where our cautious assumption is that technical options would not be induced by economic incentives; these two groups of product areas are combined in the "other" category in the figure, showing no compliance costs under either economic incentives or mandatory controls.

The transfer payments under uncompensated economic incentives are indicated by the cross-hatched portions of the bars in the figure. On average, the transfers are about fifteen times the size of compliance costs under incentives, but this relationship varies considerably from one product area to another. As a frac-

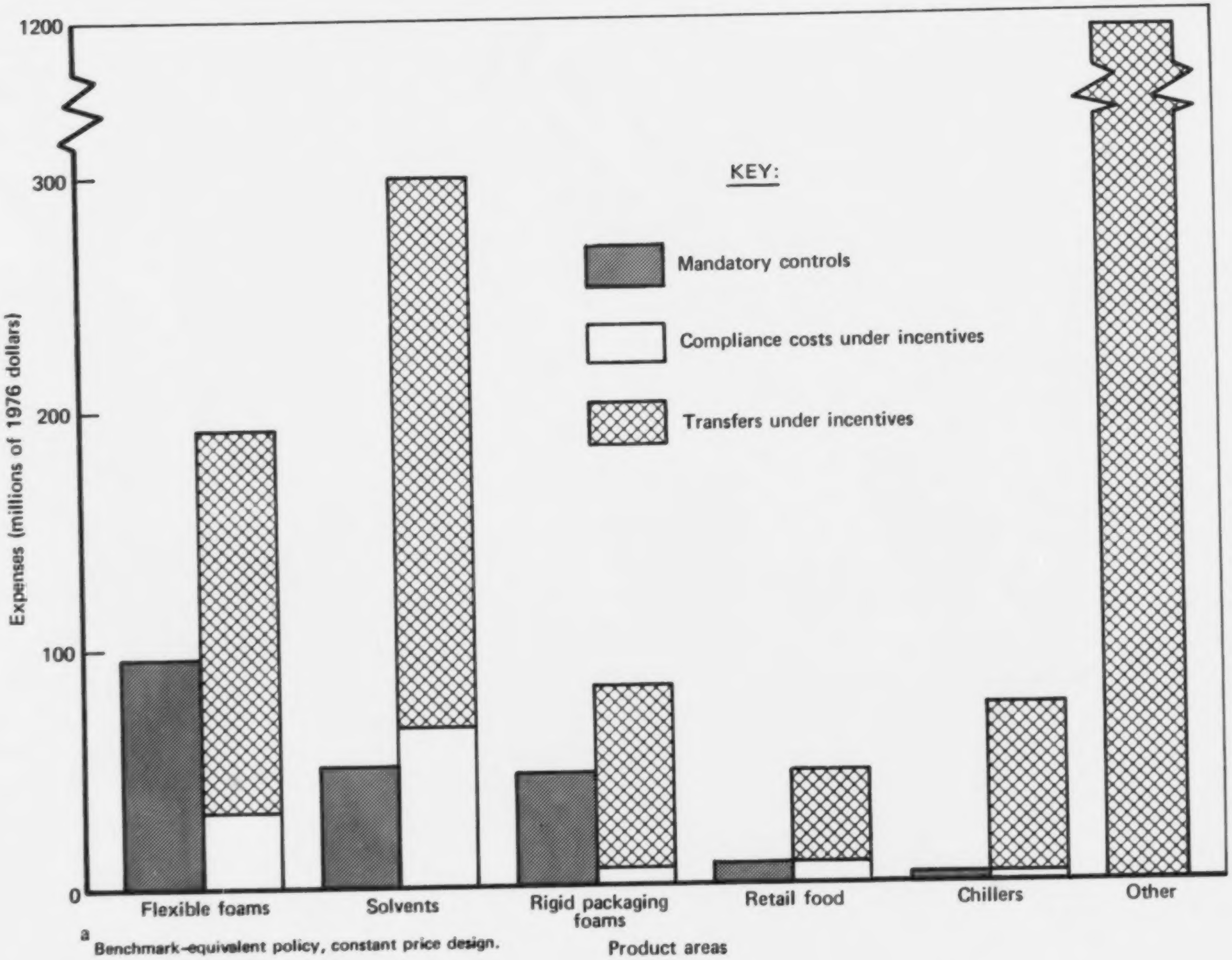

Fig. 5.1—Cumulative industry expenses under mandatory controls and uncompensated economic incentives[a]

[a] Benchmark-equivalent policy, constant price design.

tion of total expenses under economic incentives, transfer payments vary from 78 percent for solvents users to 100 percent in the "other" category. Indeed, the "other" category accounts for 66 percent of the total transfers generated by the uncompensated incentives policy.

The effects of transfer payments also vary substantially among individual firms within product areas. For most firms, the effects are the same as for the CFC-using industries as a whole: An uncompensated economic incentives policy imposes greater expenses than do mandatory controls. Even when the emissions-reducing activity required under mandatory controls is more costly than the activity induced under economic incentives, total expenses are higher under economic incentives for many firms, because the transfer payments outweigh any savings realized on compliance costs.

However, not all firms would be seriously affected by transfer payments. For example, given an uncompensated benchmark-equivalent policy, some flexible urethane foam plants will convert most (if not all) of their output to methylene chloride. For these firms, transfer payments will be a very small fraction of total regulatory costs.

Although they are the exception rather than the rule, some firms will even be better off under uncompensated economic incentives because the activity required under mandatory controls is sufficiently more costly than the activity induced by economic incentives. In the case of small polystyrene sheet producers, the benchmark mandatory controls require recovery of CFC-12, which costs nearly $1.00 per permit pound of recovered CFC. However, under the uncompensated incentives policy, this emissions-reduction activity would not be undertaken. As a result, total expenses for these firms are less under the incentives policy than under mandatory controls.

## Implications of Uncompensated Transfer Payments

Although expenditures on CFC taxes or permits (or higher CFC prices) do not constitute a real resource cost of CFC regulation, and thus do not restrict the ability of the economy to produce other goods and services, the payments are an added business expense for regulated firms. Consequently, transfer payments may be of regulatory concern for reasons that provide a motivation for seeking a compensated implementation plan for economic incentives.[7]

Uncompensated economic incentive designs will result in higher prices for final products made with CFCs than will compensated designs or mandatory controls. Under an uncompensated policy, firms and their customers bear the full burden of the transfer payments and total costs of production are higher. Consequently, final product prices will be higher. Although prices elsewhere in the economy should fall commensurately, in a trillion-dollar economy it cannot be predicted in which individual industries this effect will be noticeable. In short, the burden of transfer payments will be readily apparent, while the benefits might not be.

Uncompensated economic incentive policies increase the risk of plant closures.

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[7] In principle, the arguments for transfer payment compensation also favor compensation for compliance costs. However, transfer payments are potentially so much larger than compliance costs that a particular emphasis on the motives for transfer payment compensation is warranted.

Plant closures might occur if higher final product prices cause substantial reductions in final product demand; a second reason for a greater risk of plant closures is that uncompensated policies cause an increase in the optimal scale of production,[8] so that a given total industry output would be produced by fewer plants. Without detailed information on individual plants around the country, it is impossible to predict where plant closures caused by transfer payments might occur. However, the risk of plant closures would be greatest in industries where transfer payments are large relative to total production costs, entry and exit are not uncommon, and final product markets are stable or growing slowly.

Plant closures are an extreme manifestation of a more general consequence of regulation. Fixed investments have been made in the past in equipment, structures, and human skills that cannot be easily adapted to the new regulatory environment. Under regulation, these investments are devalued. In the extreme case, a plant is closed down, some of its equipment might be sold, but the rest is scrapped. Workers are laid off, and while they eventually find other jobs, they cannot use certain skills specific to their earlier employment. But even if a plant does not close, returns to fixed capital, both physical and human, are less under regulation than had been anticipated when the investments were made.

Devaluation of fixed capital occurs under any form of regulation, whether mandatory controls or economic incentives.[9] However, the magnitude of uncompensated transfer payments implies that the wealth loss from capital devaluation in regulated industries is much greater under uncompensated economic incentives policies than under other policy approaches. For these reasons, most firms would understandably prefer mandatory controls to uncompensated economic incentives.

## Alternative Implementation Approaches: Some That Reduce Transfer Payments and Some That Do Not

The wealth effects associated with transfer payments and their adverse impacts on the CFC user industries are not essential to an economic incentive policy design. However, it is not easy to devise an implementation plan for incentives that will effectively reduce transfers. Here we evaluate some plans that have been suggested.

**Exemptions.** Perhaps the most obvious means of reducing transfer payments is to grant exemptions from the regulation. This approach involves excluding some CFC users from the requirement to make tax payments or purchase permits.

A simple exemption policy could exclude all the applications in the "other" category of Fig. 5.1. Under the benchmark-equivalent constant-price-increment policy design, granting exemptions to all applications in that category would reduce total transfer payments by 66 percent.

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[8] Consider two policies that result in the same emissions-reducing activities, but only one of which imposes uncompensated transfer payments. The marginal cost curves are the same in both cases, but total and average costs are necessarily higher under the uncompensated policy; hence, optimal scale must be larger. Consequently, an uncompensated economic incentives policy unambiguously increases optimal scale relative to a compensated policy. Because mandatory controls do not always lead to the same emissions-reducing activities as economic incentives, the comparison of optimal scale is ambiguous. However, the sheer magnitude of transfer payments relative to mandatory control compliance costs suggests that uncompensated economic incentives cause increases in optimal scale relative to mandatory controls.

[9] Devaluation of fixed capital occurs in regulated industries, but the devaluation caused by transfer payments is offset by an increase in the value of capital in unregulated sectors of the economy.

Although exemptions could dramatically lower transfer payments, this approach is seriously flawed. An important defect of an exemption policy is that the cost of using CFCs is not increased for exempted applications, thus eliminating the incentive to develop and use technical options for emissions control. For some products in the "other" category, there are technical options that are not taken into account in the analysis simply because the costs of the options are unknown, but in other products, there are no technical options currently. That is caused, at least in part, by the fact that historically the price of CFC has not reflected the potential ozone damages of CFC emissions. Under the stimulus of higher CFC prices, these industries can be expected eventually to develop products or production processes that are less dependent on CFCs.[10]

The nonaerosol CFC applications that do not appear to have technical options currently—of which foam insulation and refrigeration products are the largest—account for the largest fraction of projected CFC use over the next decade. These rapidly growing applications are expected to use 3.2 billion permit pounds of CFC from 1980 through 1990. As a result, exempting these uses would be tantamount to eliminating incentives for emissions reductions in the product areas where future emissions levels are expected to be the greatest.

A second shortcoming of allowing exemptions is that the monitoring costs required to achieve an emissions-reduction goal could be dramatically increased. Suppose, for example, that CFC-11 in rigid urethane insulation is exempted, but CFC-11 in flexible urethane foam is not. To enforce the policy, it is necessary to determine where a pound of CFC-11 is actually used. It may be extremely costly to prevent black market activity, whereby exempt users purchase CFCs at the supply price and resell them in regulated markets at a higher price.

A third shortcoming is that exemptions would do nothing about the large transfer payments in product areas that are expected to implement technical options for emissions control. These product areas cannot be exempted without reducing the effectiveness of the incentives policy, yet the transfer payments in these product areas would have the price and plant closure effects outlined above.

In principle, it is possible to design a compensation approach that does not have the shortcomings of exemptions. In practice, it is no simple matter to design an approach that eliminates a major portion of transfer payments without reducing or distorting the basic incentives for emissions control that the larger policy is designed to create. The design of a compensation approach is far beyond the scope of this study, but a few comments on the subject serve to illustrate the opportunities and possible pitfalls involved.

**Direct Allocation to Users.** Under a marketable permits policy, a promising compensation approach would be to allocate permits to users directly, without requiring permit payments. If, fortuitously, the allocation of permits in each time period were exactly equal to the number of permits each firm would buy under an uncompensated policy, direct allocation would eliminate transfer payments altogether. Even if the initial allocation were imperfect, the magnitude of transfer payments would be reduced to the extent that fewer permits would be bought and sold; moreover, all of the transfer payments would remain within the group of CFC-using industries, with some firms whose allocations were larger than necessary selling permits to firms whose allocations were inadvertently too small.

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[10] This argument is essentially a restatement of the second fundamental law of demand: Long-run demand schedules are necessarily more elastic than short-run demand schedules.

Direct allocation of permits does not eliminate the incentive for emissions reductions because the permits continue to have value in the aftermarket (the market in which user firms buy and sell permits to each other). Consider, for example, a firm that has been allocated 1,000 permits for which the aftermarket price is 50 cents each. If the firm can reduce CFC use by 250 permit pounds at a total cost of $50, the firm will do so because it will then be able to sell 250 permits and receive a total revenue of $125 from the sale. More generally, the aftermarket should yield the same price for permits under direct allocation as under an uncompensated policy, and the final distribution of CFC use among firms should also be the same. Only the magnitude of transfer payments would be affected by direct allocation.

Using a tax policy, a comparable implementation approach to direct allocation is to grant each firm an entitlement to buy a prescribed amount of CFCs without paying the tax. In this case, user firms would be able to resell the CFCs in the user aftermarket if the initial entitlement proved to be too large—or to buy CFCs from other user firms if the entitlement were too small. The price at which CFCs would be traded in the aftermarket would be equivalent to the CFC suppliers' price plus the amount of the tax, but firms that sold CFCs in the aftermarket would receive the full amount of the aftermarket price. As in the case of direct allocation of permits, the incentive to conserve on CFC use is retained, but the magnitude of transfer payments is lower than under an uncompensated policy.

**Compensatory Reimbursement.** While directly allocating permits to users reduces the effects of transfer payments by preventing them, another compensation approach is to reduce the effects by reimbursing users for their transfer payments. However, it is not possible simply to pay firms back for their expenditures on taxes or permits without eliminating the incentives for reducing emissions. Instead, it is necessary to reimburse firms on some basis other than the actual amount of transfer payments they make.

One approach we have considered is to make compensatory payments to firms on the basis of their final product output. (The payments would be based only on final product output and not on CFC input, so that reducing CFC use would continue to be just as profitable as under an uncompensated incentives policy.) If final product demand is perfectly inelastic, then the compensation payments could be designed to reduce final product prices enough to offset the price increases that would derive from the CFC transfer payments. However, if there is any elasticity to final product demand, reducing the product price would cause final output to increase, generating increased demand for CFCs and ultimately raising the permit price or the tax required to achieve a targeted level of emissions reduction. Whereas the assumption that final product demand is perfectly inelastic serves well in yielding cautious estimates of the emissions effects of incentives policies, the assumption could be a disservice to the design of a reimbursement policy for transfer payment compensation, and should not be relied upon in that context. In the absence of perfectly inelastic final product demand, a final product rebate system is a less promising technique for compensation.[11]

**Direct Allocation to the CFC Producers.** Because direct allocation to users appears to be a promising way to reduce transfer payments, it might appear that direct allocation of permits to the producers would be equally effective and simpler to implement because there are so few producers for whom the allocations would have to be determined. Unfortunately, direct allocation to the CFC producers will not reduce transfer payments. Instead, the prices that users would be willing to pay for permits will be paid to the CFC producers; the producers will receive large revenues from the sale of permits, but the CFC users will still face higher expenses for the permits they buy and will have to raise their product prices and face the risk of going out of business if consumers are unwilling to pay the increased prices or if the optimal scale of production is significantly increased. In summary, we expect the outcomes of direct allocation to producers to be very similar to the outcomes of an uncompensated policy, except that the producers will receive the transfer payments from users.

**Quotas Without Permits.** Because the sale of permits generates transfer payments, some readers might mistakenly conclude that transfer payments can be eliminated under a quota policy by eliminating permits. The quota restricts the availability of CFCs and, in the absence of permits, some other mechanism will necessarily arise to allocate the CFCs among competing users. A likely outcome is that the CFC producers will raise their prices. If the new CFC prices match the sums of producer charges and permit prices that would arise under a permit policy, the transfer payment outcome would be precisely the same as under a permit policy with direct allocation to the producers: Total transfers would be maximized and the entire amount of the transfers would be received by the CFC producers.

In order to implement a CFC quota without permits, it would be necessary to establish production quotas for the individual CFC producers. It will be difficult to select a formula for allocating production among the producers that will be acceptable to all of them.

The political issue of how to allocate production among the CFC producers is also raised by a decision to allocate permits directly to the producers. In the absence of permits, however, there is an added potential pitfall in allocating production. For the use of resources to be efficient (i.e., least costly to the economy as a whole), the distribution of CFC production among the producers should reflect the least costly means of production; if the individual producer quotas do not match the most efficient distribution of production activities, and if the producers cannot trade production rights under their quotas, then the use of resources under a quota without permits will be more costly to the economy than necessary.

Because a policy that uses quotas without permits requires quotas for the individual producers, the policy is not much simpler to implement than one that involves direct allocation of permits to the producers. Furthermore, quotas without permits could cause production inefficiencies. Consequently, there is little to recommend quotas without permits over direct allocation of permits to the CFC producers.

**Concluding Remarks.** The implementation issues associated with the design of compensated economic incentives policies should not be underestimated. Both the basis and the formulas for compensation raise politically sensitive and economically complex issues. They are politically sensitive because of their obvious and direct implications for the distribution of wealth among the CFC user and producer industries. They are economically complex because it is no simple matter to devise specific rules that prevent distortions in the policy that might thwart the economic incentives it is intended to create.

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[11] A further disadvantage of compensatory reimbursement is that it appears administratively difficult. Legislative authority might be required.

Ultimately, the resolution of the implementation issues raised by transfer payments may be one of the most critical policy choices required by CFC destruction of the ozone layer. As Sec. IV concludes, if relatively low emissions-reductions levels are required, economic incentives and mandatory controls are both viable policy choices. However, if emissions reductions beyond the relatively limited capabilities of mandatory controls become necessary, the policy choice appears to be between economic incentives and outright CFC bans, which are very costly. For example, in the rigid foam insulation product area, where the data to assess some of the effects of a ban are available, the analysis in Sec. III.C suggests that a ban implemented in 1980 on CFCs in this product area alone would impose annual losses, measured in terms of increased energy consumption, equivalent to 152 million barrels of fuel oil by 1990.

Despite the advantages of economic incentives for reducing the real resource costs of regulation and achieving substantial emissions reductions, the adverse impacts on user industries from an uncompensated incentives policy may not be acceptable. If this is the case and substantial emissions reductions are required to prevent serious environmental damage, the achievement of regulatory goals may rest on the ability to design a compensated policy that does not distort incentives for low-cost emissions reductions.

## OTHER REGULATORY ISSUES

The remainder of this section surveys a broad range of regulatory issues, including the side effects of policy, operational features of different policy approaches, and a variety of implementation details. Because they are less familiar tools for environmental policy, economic incentives policies are the focus of attention in much of what follows, and a brief description of the operation of tax or permit policies is a useful prelude to the discussion.

### Operation of a CFC Tax

Aside from the special features that might be introduced as a means of transfer payment compensation, a tax on CFCs would be instituted and operated like other sales (excise) taxes. The tax would be added to the purchase bill for CFCs, paid by users to the CFC producer, and transmitted by the producer to the revenue authority.

Because the ozone depletion potential per pound of emissions varies among the CFCs, the tax rate would vary among the CFCs. The illustrative case considered in this study bases the desired tax rate on the chlorine content per pound of emissions, but exempts CFCs (such as CFC-22) that are not fully halogenated. A more precise tax formula could be developed from recent scientific evidence on ozone depletion potential.[12] Such a formula could be extended to include taxes on all CFCs. The only exemptions from the tax that would be recommended by efficiency and effectiveness criteria would be for CFCs used in applications where there are no emissions, such as when the CFC is used as a precursor for producing other chemicals that do not deplete ozone. In principle, the tax could be used as an economic disincentive even for CFC use in aerosol applications; however, our analysis assumes that the ban on aerosol applications would be retained now that it has been implemented.

All the tax rates specified in this study are measured in constant dollars. The tax would vary in dollar terms under inflation. Moreover, the tax rates specified here assume that the prices of all CFCs (except CFC-113, as explained in Sec. III.B), will remain constant in real terms over the period 1980 through 1990. If CFC supply prices change in real terms over the period, the real tax rate would have to be revised to meet the emissions reduction target.

## Operation of CFC Marketable Permits

Under the policy designs considered in this study, a permit is a piece of paper that authorizes the holder to purchase a specified amount of CFCs for use in specified applications. Ideally, the face value of the permit would vary in terms of CFC pounds depending on the ozone depletion potential of each CFC. Although CFC-22 is exempted from the permit policy designs considered here,[13] in principle the permit could be specified to cover all CFCs. Ideally, only those applications where CFCs are not emitted (e.g., where the CFC is a precursor in producing other chemicals) would be exempt from the policy; however, the existing ban on aerosol applications already implies that the permits would not authorize the use of CFCs as aerosol propellants.

The permit would have a specific time interval during which CFC purchase is authorized and a maturity date at which the interval ends. The authorization interval and the mix of maturity dates for outstanding permits should be chosen according to two basic principles. First, the authorization interval should be long enough to allow firms to buy and sell permits as needed to insure that demand and supply are equalized. Second, the interval should be long enough and the mix of maturity dates should overlap enough so that there are not major swings in the permit price from one issue to the next because of short-term fluctuations in demand.

The permits could be used to purchase CFCs from any producer. Thus, the producers would compete for CFC sales as they do now, and the quota on sales would automatically be allocated among producers by the market without regulatory intervention.

Permit design features can influence the credibility of the permit policy. For example, a document design that (like the design of paper currency) inhibits forgery is more likely to encourage the perception that the documents are legal tender whose legitimacy will be enforced. Similarly, a policy that involves releasing some permits in advance of their authorization interval would help encourage the belief that the regulatory agency intends to stick to forestated goals for quota levels in future years. For example, permits could be sold in 1985 to cover authorization periods in 1986, 1987, and so on.

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[12] Changing the permit pound formula in this way would affect the policy outcomes estimated here.

[13] Except insofar as it is a component of CFC-502.

In contrast with taxes, a permit policy would not have to be revised to achieve a specified emissions target if the money or real supply prices of CFCs vary over time. The permit market would adjust automatically to establish the permit price that brings demand into equilibrium with the supply of CFCs under a given quota.

### Implementation and Enforcement Costs

Implementation costs are defined here as the costs to the regulatory body of the many activities that are undertaken before the promulgation of regulatory policy. For a new source or retrofit performance standard, for example, the activities include engineering data collection, economic analysis, publication of the standard, public participation, government review, and so on.

EPA has performed a preliminary calculation of what it would cost for the engineering data collection, economic analysis, development of regulatory options, and publication of standards for new source performance standards covering the major CFC nonpropellant applications.[14] The estimate of these costs is about $1 million for activities that would take about four to five years to perform.

The implementation costs for a novel policy approach, such as taxes or marketable permits, would probably be greater than for mandatory controls because it takes time and some learning-by-doing to develop the bureaucratic mechanisms that would support the new policy approach. Once the policies become familiar, however, their implementation costs would fall. Aside from startup costs, uncompensated transfer payment systems should be inexpensive to implement because they are so simple to operate.

Major differences in regulatory costs between mandatory controls and economic incentives are likely to arise with regard to enforcement. Although there are no estimates of the costs, a brief description of what is involved under the alternative policy strategies shows why they should differ. Under economic incentives, enforcement involves monitoring the production and sales rates of a handful of CFC production facilities to assure that production corresponds to permit remittals or tax revenues. Under the benchmark mandatory controls, enforcement involves monitoring activities at individual point sources of emissions—at least at enough of them to convince users that evasion will probably be discovered. Even if we assume that all the individual point sources can be found—by no means a simple task in itself—the number of enforcement sites is so large that monitoring would be very costly.

The benchmark controls governing the behavior of chiller and retail food refrigeration manufacturers would not be too difficult to enforce because there are only five firms or so in each business—but the emissions reductions from the controls on these products are also relatively small. Thermoformed polystyrene sheet producers would contribute more to the benchmark emissions reduction and are somewhat more numerous; there are as many as 30 plants currently, and 45 to 50 plants might be in operation by 1990. Monitoring recovery and recycle in flexible foams plants is still more troublesome, with over 70 slabstock plants and more than 20 molded foam plants currently in operation, and the number growing fairly rapidly. Finally, monitoring equipment standards in the 5,000 plants that currently use CFC solvents would be very costly—and the number of plants is expected to grow at perhaps five to eight percent per year until 1990. Thus, the number of sites to be monitored under mandatory controls is several hundred times as many as the monitoring sites for economic incentives policies.

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[14] The EPA estimate is essentially a simple multiple of the costs of previous regulatory projects referring to an individual product area. The particulars of the CFC benchmark mandatory controls are not reflected in the estimate.

As noted later in this section, one possible enforcement problem raised by economic incentives policies might be prevention of illegal CFC imports.

## Setting Goals and Establishing Confidence

Previous experience indicates that mandatory controls are costly and time-consuming to modify. In contrast, firms may perceive tax rates or quota levels as highly variable, subject to regulatory whim or political manipulation. If so, firms might be reluctant to undertake long-term investments that would reduce emissions for fear that future regulatory action would make the investment obsolete or reduce its cost-effectiveness. Thus, establishing and maintaining long-range policy goals can contribute to the success of an economic incentives policy strategy.

Because economic incentives policies rely on decentralized decisionmaking, there is some uncertainty about the precise market outcomes under the policies. The nature of the uncertainty differs in a critical respect between taxes and permit quotas. With taxes, the prices users must pay to obtain CFCs are known, but the emissions outcomes of the price policy are uncertain. Marketable permits policy, on the other hand, establishes a definite quota on use, and emissions will be determined within a small confidence interval.[15] Consequently, if the primary goal of policy is to achieve a particular CFC use or emissions target, tax rates are far more vulnerable to revision than is a marketable permits policy.[16]

Revising tax rates to arrive at an emissions target (or to achieve a new target) is likely to introduce uncertainty that can distort the effects of the policy. Revising the quota under marketable permits would do likewise, but there is another regulatory approach that would enhance industry confidence while maintaining flexibility in the emissions target: The regulatory agency could retain the stated quota, but buy back permits from the market to achieve a lower emissions goal. The CFC producers would still be subject to variable output levels because of the policy action, but at least the CFC users would be reimbursed for the regulatory revision.

Of course, permit prices are variable because of changes in demand conditions even if a quota is maintained. However, industry is continuously subject to the variability of natural market forces and has techniques for predicting how those forces will vary over time. The issue at hand is how the regulatory agency can best establish confidence in *its* future behavior—and publicized long-range quota goals combined with a marketable permit buy-back policy is one way of encouraging industry confidence.

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[15] Most of the emissions reductions under the economic incentives policies evaluated here are prompt emissions. Hence, use reductions are nearly equal to emissions reductions.

[16] The estimates of permit prices in this study are far more likely to be excessive than not. (See Sec. II.)

## Methods for Releasing Permits

The regulatory body can release directly allocated permits simply by allowing an authorized representative of each individual firm to claim the permits or by mailing them to the firm's headquarters. Release of permits that are sold can be carried out in many alternative ways.

One approach would be a centralized auction: At a specified place and time, the regulatory body puts blocks of permits up for bid by all eligible market participants.

Under an English auction, bids begin at the first price designated by a bidder, and the sale is consummated when no bidder is willing to exeed the last bid price. Under a Dutch auction, an initial price is specified by the auctioneer, and the price is revised downward until some bidder is willing to accept the block of permits at the stated price. If the permit demand schedule has regions of inelasticity, a Dutch auction can result in a higher bid price than an English auction (Stigler, 1966). Given a quota on the total permits available, a lower bid price is desirable because it reduces the transfer payments for permits. Hence, the English auction has the advantage that it could impose lower transfer payments if there are regions of permit demand inelasticity. Moreover, the English auction formula is more familiar in this country than is the Dutch auction formula.

Auctions, whether English or Dutch, bring together market participants in a single event in which they can observe each other's behavior. This might encourage collusive behavior, as explained below. In contrast, it might be possible in principle to release permits continuously or at frequent intervals through a permit exchange similar to (and perhaps in conjunction with) a securities or commodities exchange. This option is best evaluated by experts in securities markets.

## Participation in the Permit Market

Eligibility for participation in the permit market can be circumscribed by regulation, though there are few clear reasons for doing so, and enforcement of eligibility would be difficult. The more participants there are in the market, the greater is the likelihood that it will yield a competitive outcome. Allowing CFC users to participate assures a large number of active buyers and sellers.[17] Also allowing producers to participate grants them an opportunity to relieve some uncertainty about their production levels; in effect, they would sell permits along with the CFCs, and then immediately turn in the permits for collection by the regulatory agency. Users would buy from the producer who could offer the lowest combined price for the CFC and the permit. The producers would have little incentive to pay more for permits than they expect users to be willing to pay, and because users would also be able to participate in the permit market directly, the producers could not pay less than the competitive permit price.[18]

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[17] Whatever the eligibility rules, we presume distributors would be allowed to participate at least insofar as they would be allowed to handle a quantity of permits commensurate with the amount of CFCs in each distributor transaction.

Allowing participation by groups other than producers and users is not unjustified. Environmental groups could conceivably wish to enter the market to buy permits and prevent emissions that would otherwise be allowed under the quota. The willingness of such groups to make the necessary expenditures (and their ability to raise support for the activity) would be an indication that the existing quota level does not fully reflect the publicly perceived hazard from CFC emissions relative to other environmental problems. Notably, there is as yet no particular environmental protection constituency for which CFC emissions is the exclusive focus of attention, and neither of two prominent environmental organizations with more general concerns that were contacted informally expressed any interest in participating in a CFC permits market.

A futures market for permits might arise, and some participants in this market might be neither users nor producers of CFCs. A futures contract is one in which a market participant agrees to buy or sell permits that will be released at a future date. The futures contract buyer and seller agree on a prespecified price for the permits to be delivered. When the pertinent permit issue is released, the seller in the futures contract must buy enough of the new issue at the prevailing price to fulfill the futures contract. If the prevailing price exceeds the prespecified price, the futures seller loses money on the transaction—but if the prevailing price is lower, the seller earns a profit. Futures contracts provide a valuable service, offering an opportunity for certain market participants to absorb risks associated with uncertainties about future permit prices, and offering other participants the opportunity to reduce their risk-taking. Thus, there is no clear gain—and maybe some disadvantage—in restricting futures trading.

## Assuring "Fair Practices" in the Permit Market

Historically, the federal government has taken an active role in monitoring and controlling the operations of commodities and securities markets to limit such abuses as fraud, price-fixing, excessively risky credit practices, collusion, and counterfeiting. A review of the state of the art in governmental oversight in these areas is far beyond the scope of this study, but it is clear that the formulation and implementation of a CFC permit market can benefit from readily available expertise in these matters. What remains to be considered here are the specific properties of a CFC permit market that might encourage or discourage collusion among market participants or predatory behavior.

Collusion refers to organized behavior by a group of firms to control the permit price. The goal of collusion would be to prevent the permit price from reaching the level it would attain in a freely competitive market. Collusion is unlikely in the aftermarket for permits because there are so many potential participants who would be willing to pay the competitive price for permits in order to remain in business. For the same reason, collusion is unlikely in the market for newly released permits if they are released through a system similar to a securities exchange where bidding is continuous and repetitive. Collusion is perhaps more feasible under an auction where large blocks of newly released permits are made available and firms are brought together at a specific time when each can observe the bids of other market participants.

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[18] There do not appear to be any advantages from allowing only producers to participate in the permits market, and a possible disadvantage is that it would encourage collusion, as discussed below.

The prospect of collusion is not unfamiliar in commodities and exchange markets, and mechanisms for limiting collusion have been devised for situations similar to those of a CFC permit market. The major point to be made in the CFC context is that collusion does not negate the effectiveness of the permit quota in limiting overall emissions. Moreover, so long as the permit aftermarket is competitive, collusion does not affect the opportunity cost to users of creating CFC emissions. Thus, collusion does not necessarily (or even probably) mean that a CFC permit policy becomes ineffective or inefficient. Rather, collusion—if it occurs—implies only that some firms might unfairly reap the reward of buying permits at an artificially low price and selling them at the competitive price.

Predatory behavior arises if some firms are able to buy up permits to force their competitors out of business. The potential for predatory behavior appears very small, so long as all regulated CFCs are included in a single permit market. If a substantial share of the permits is directly allocated to users, the possibility of driving users out of business by restricting their access to CFCs is circumscribed directly. If the permits are sold for all CFCs, a predator could restrict access by his competitors only by buying up a very large fraction of all the permits for all CFCs, not just the CFC used in the predator's industry.[19] For example, in 1980 a predator would have to buy up over 450 million permits to corner the market for a single year. Not only is such predatory behavior extremely costly to the firm (since it would have to outbid all other bidders), but the activity would be fairly easy to monitor and, provided the permit policy contains sanctions against such behavior, the activity would be fairly easy to stop. Finally, like collusion, predatory behavior does not prevent the permit program from meeting its emissions-control goals.

In summary, neither collusion nor predatory behavior appears likely in the CFC permit market, neither would limit the emissions-reducing potential of a permit policy, and both appear readily amenable to the same sorts of regulatory control that are currently available for other commodities and securities markets.

## Combining Direct Controls and Economic Incentives

As a general principle, imposing mandatory controls in addition to using economic incentives would detract from the desirable features of economic incentive policies. Mandatory controls restrict firms to using certain technologies or undertaking certain emissions-reducing activities even when other emissions-control activities (those that would be encouraged by economic incentives) are more cost-effective.

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[19] Recall that a permit can be used to buy a specified amount of any regulated CFC for use in any application. Thus, for example, a small flexible foam producer could buy permits from a producer of refrigeration devices even though the CFCs used in the two applications differ. Such cross-industry transactions might be facilitated by CFC distributors and producers, who have an incentive to assist in this process in order to increase their own CFC sales.

At present, the use of economic incentives would already occur in combination with the existing ban on aerosol applications of CFCs. It is possible that economic incentives policies of the sort examined here would have induced substitution away from CFC aerosols except for the cases that are exempted under the current ban. If so, the outcome of the combined policies would not differ from the optimal outcome under a pure incentive policy that covered all CFC applications. More generally, however, it should be expected that imposing mandatory controls in addition to economic incentives would affect CFC market and emissions outcomes; if not, there would be no need to impose the mandatory controls because they would add nothing to the effectiveness of the policy.

There is a basis in economic theory for introducing mandatory controls in addition to economic incentives in specific situations. This would arise if there were a market imperfection that prevents economic incentives from functioning properly. The only example we have identified from a CFC product area that might fit this criterion occurs in mobile air conditioning. There, final product consumers may not take into account the cost of CFCs used in mobile air conditioning service and repair when they choose a vehicle containing an air conditioning unit.[20] Hence, the system manufacturers do not face an incentive to design systems that have low repair and service emissions (unless, fortuitously, the system designs reduce costs of production or initial charges). Because economic incentives may not be fully effective in this situation, mandatory controls to achieve better system designs might be warranted. Our analysis presumes that economic incentives would not affect CFC use or emissions in this product area, and because of the lack of adequate data, there are no controls on mobile air conditioners in the benchmark set of mandatory controls.

Another situation where a combined regulatory strategy might be used is where the emissions-reduction activities that would be induced by economic incentives impose risks of other worker, consumer, or environmental hazards. As explained later in this section, product areas in which this is a potential problem might be exempted from the economic incentives policy. Then, mandatory controls to require use of a different (and more costly) means of emissions reduction might be imposed on the product area.

### Import and Export Policy

The economic incentive and mandatory control policies examined here operate primarily in the domestic market. However, concerns of equity and effectiveness imply that some regulatory action be taken with regard to import and export markets.

Unlike mandatory controls on the behavior of users, economic incentives policy requires enforcement to prevent illegal imports of CFCs. Under taxes or permits, imports of CFCs would have to be subject to the policy in order to prevent unfair competition with domestic producers and to preclude evasion through import substitution.

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[20] As Sec. III.D explains, the market imperfection under consideration is due either to imperfect consumer information or the existence of a tied sale (i.e., the consumer purchases a vehicle and an air conditioning unit jointly).

Under either economic incentives or mandatory controls, both of which increase the costs of producing domestic final products, imported final products made with CFCs should be taxed.[21] Operationally, selecting an import tax rate on a final product that correctly reflects the effect of regulatory policy on domestic final product prices is extremely difficult. However, the problem of devising the appropriate tax is essentially the same, no matter whether mandatory controls or economic incentives are used. The only two product areas where imports are not naturally limited by transportation costs are mobile air conditioners and freezers. These are the only products where import taxes appear warranted under the policies analyzed in this study.

Export policy raises somewhat different issues that can be cited here but cannot be resolved without analyzing foreign CFC markets. Exports of CFCs offer domestic producers an opportunity to maintain production levels despite domestic regulatory policy; whether the exports increase foreign emissions of CFCs depends on the extent to which they add to (rather than substitute for) CFCs that would be produced by foreign manufacturers. Exports of final products made from CFCs also have uncertain effects on world emissions. To some extent, the availability of U.S.-made products may increase the foreign consumption of CFC products, thereby tending to increase total world emissions. On the other hand, U.S. products that are produced under domestic regulation might substitute for foreign products that would be produced under emissions conditions that are uncontrolled, thereby reducing world emissions. Which effect prevails determines whether export controls for final products made with CFCs would help reduce world emissions.

### Inventory Behavior

Suppose that CFC users attempt to build up CFC inventories to assure against shortages, particularly under uncertainty about future policy changes. Under a permit policy, inventory buildup is feasible because enforcement governs the use of permits to purchase CFCs but would control actual use only with great difficulty. However, under a permit policy, inventory buildups would imply rising permit prices, thus exerting a moderating influence; a widespread attempt to increase inventories would quickly become too costly to maintain.

In contrast, inventory buildup under a tax policy would not be costly unless the tax rate were revised upward in response to observed inventory activity. To limit this activity, it would be necessary to monitor final product output and CFC production levels, and to raise taxes whenever the data suggest rapid inventory growth. This approach, however, has the undesirable side effect of reducing confidence in the policy, perhaps creating further pressure for inventory-building activity. Thus, this is an area where permit policy appears to have a definite advantage over tax policy.

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[21] Import taxes are appropriate even under a domestic policy based on quotas with permits. The tax should be set to have the same effect on imported product prices as the permits have on domestic product prices. If the imported product contains CFCs that will be emitted after importation, the domestic quota on CFCs will already apply to CFCs used to replace the emissions from imports. CFC losses that would not normally be replaced are likely to be too small to be concerned about.

## Risk Tradeoffs

In some product areas—most notably flexible foams, solvents, and sterilants—a significant opportunity for reducing CFC emissions lies in substituting other chemicals for CFCs. The alternative chemicals may impose environmental or worker health hazards of their own. In the absence of controls on the alternative chemicals, policies that work well in reducing the ozone depletion risk from CFCs will increase the risk of other hazards.

This is true under mandatory control policies as well as under economic incentives. For example, 40 percent of the CFC emissions reduction for flexible foams under a recovery and recycle mandate occurs because some firms would find it less costly to convert to methylene chloride than to comply directly with the CFC control. The difference between the two types of policy is a matter of degree: Economic incentives rely more heavily on chemical substitution because that is less costly in many cases than alternative means of CFC emissions control. Under any policy strategy, the attempt to control substitute chemicals will make the policy less effective in reducing CFC emissions than the estimates given in this study, which assumes no other changes in regulatory controls for non-CFC chemicals.

A regulatory agency can attempt to control hazards from substitute chemicals directly, using economic incentives or mandatory controls in the substitute chemical product areas. Alternatively, substitution can be controlled within the context of CFC policy itself. Under a mandatory controls strategy on CFCs, the only option for preventing chemical substitution would be to forgo controls that would indirectly encourage substitution. Economic incentives policies have greater flexibility. The tax rate or face value of the permit can be adjusted so that the incentive for substitution in certain applications is reduced. Equivalently, the regulatory body could rebate a fraction of the tax or permit payments to user firms that can demonstrate that they have limited their use of alternative chemicals.[22]

As a general matter, economic incentives policies can be designed for a wide variety of chemicals such that the use of all of them is reduced in some desired proportions. Thus, economic incentives policies are particularly suited to situations where policies with regard to many different products or chemicals are interrelated. In contrast, mandatory controls are relatively inflexible in situations where there are tradeoffs among different types of environmental or health and safety risks.

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[22] These rebates differ from those described earlier for reducing transfer payments. The earlier rebates would be paid in amounts that are independent of changes in CFC use. The amount of the rebates mentioned here would vary with the level of CFC use, and thus would affect chemical substitution and the firm's choices with regard to other techniques for reducing CFC use.

# VI. POLICY ISSUES AND OPTIONS

This section presents some of the insights that have emerged from this research concerning the major policy issues for CFC nonaerosol regulation. Setting a goal for emissions reductions is a primary regulatory decision. Closely related is the choice among alternative policy strategies—voluntary action, mandatory controls, economic incentives, or CFC bans—to use in meeting the emissions goal. If mandatory controls or CFC bans are selected, further choices include whether to grant exemptions to individual firms or product areas, and what level of enforcement activity to pursue. If incentives are chosen, important associated decisions are whether to use taxes or quotas (and whether to use permits), and whether to engage in compensation. Although all these matters are touched upon in this section, the discussion focuses primarily on incentives policy strategies because these are far less familiar policy tools than mandatory controls.

## SETTING GOALS

To a large degree, setting a goal for emissions reduction involves making a tradeoff between the costs of regulation and the social, economic, and environmental benefits from protecting the ozone layer. This study has not addressed benefits estimation, but we can specify how costs vary with the level of emissions control achieved. Figure 6.1 illustrates the relationship between costs to the economy as a whole (compliance costs) and the degree of emissions control. Emissions control is measured as a percentage reduction in cumulative U.S. emissions over the coming decade and, alternatively, as a percentage reduction in cumulative worldwide emissions achievable by unilateral U.S. policy action.[1]

The figure illustrates costs and effectiveness for all the policy strategies except voluntary action, which is omitted because the cost and effectiveness of a voluntary program are especially uncertain. Under the simplest voluntary program, one in which policymakers merely request industry cooperation, costs to industry are likely to be lower than under any of the alternative policy strategies; firms cannot successfully compete if they take costly actions that are not required of their competitors, so firms are not likely to take costly actions. And, because there are limits to the emissions reductions that can be achieved at very low costs, the effectiveness of voluntary action is likely to be less than under alternative policies. Some types of voluntary programs—those in which the regulatory agency takes the lead in developing new technology or providing information services to industry—might be somewhat more effective in reducing emissions because the regulatory agency itself would be absorbing some of the costs associated with emissions control. In this case, the true cost to the economy includes not only the costs borne by

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[1] An important regulatory issue that cannot properly be assessed in this study is the likelihood that—and extent to which—regulatory action in the United States would induce or encourage foreign nations to take action as well.

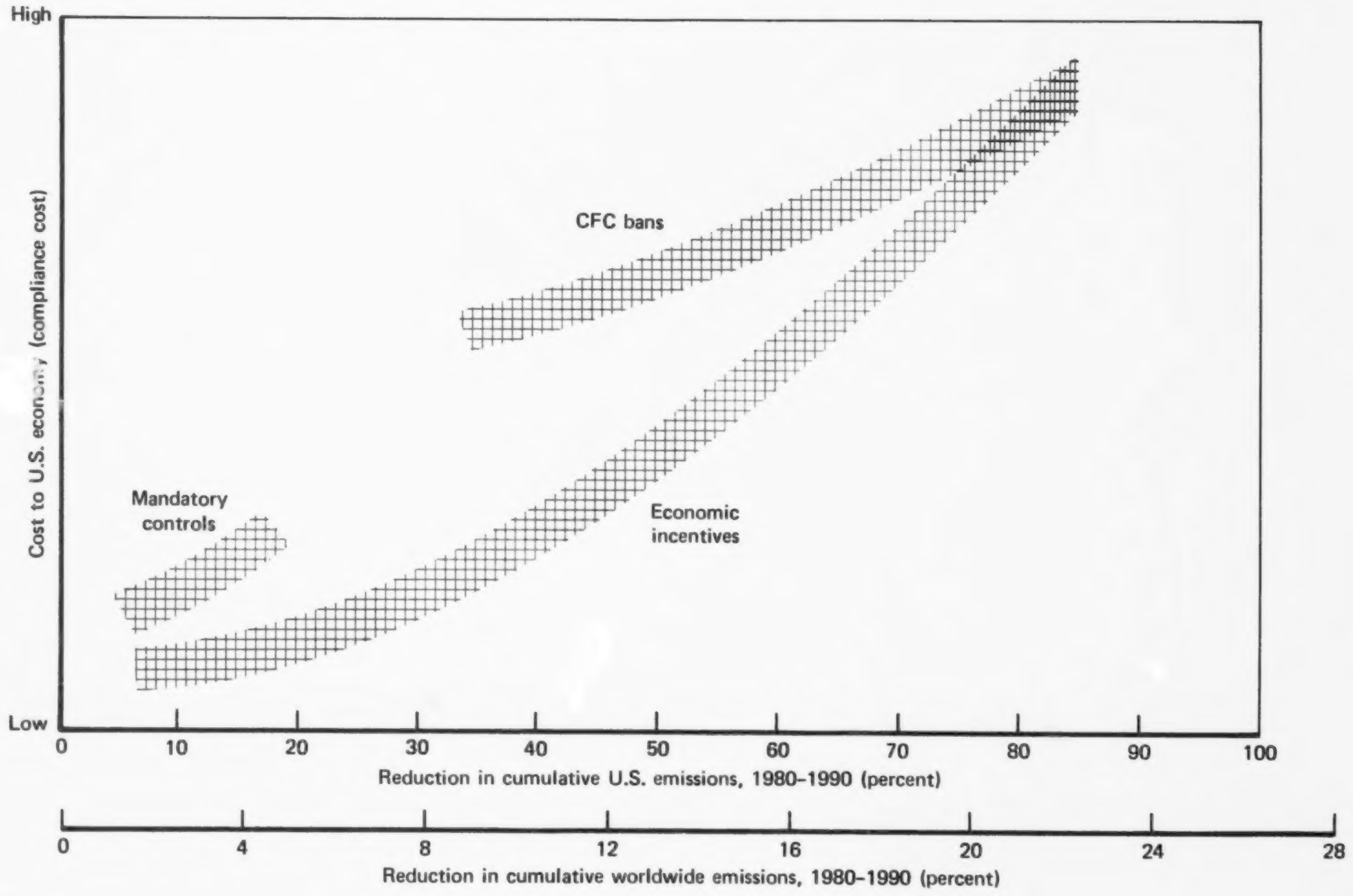

Fig. 6.1—Cost and effectiveness of alternative U.S. policies

industry but also those incurred by the regulatory agency, and any improved effectiveness of the voluntary program would derive from its higher cost to the economy as a whole. Notably, even a policy program based on developing and disseminating new technology is not likely to yield its greatest emissions improvements prior to 1990 because it takes time for industry to respond to new technological developments.

As shown in Fig. 6.1, compliance costs of mandatory controls are moderate, and emissions effects are modest; the benchmark controls would reduce cumulative U.S. emissions by 15 percent and worldwide emissions by three percent. The effectiveness and costs of mandatory controls can be varied by changing the set of controls, changing their implementation dates, granting exemptions, or choosing among various levels of enforcement activity. But however they are implemented, mandatory controls that require firms to use specific techniques for controlling emissions will have quite limited effects on cumulative emissions between now and 1990 because the technologies that are already available commercially are limited. Technologies that are on the drawing boards could prove quite effective in reducing *annual* emissions by the end of the decade, but the time necessary to bring those technologies to the commercial stage and then to carry out the regulatory steps necessary to implement mandatory controls implies that they will contribute little to emissions reductions for at least a few years. As a consequence, even if all the unproven technologies that appear promising live up to expectations, it is unlikely that *cumulative* U.S. emissions over the next decade could be reduced as much as 40 percent by means of mandatory control policy.

It would be possible to achieve higher levels of emissions reduction by banning the use of CFCs in one or more applications. While we have not researched the use of CFC bans, their greater effectiveness surely implies that they would be far more costly than the mandatory controls. Also, the maximum cumulative emissions reduction that could be achieved even by a total and immediate ban on all CFC use would be only 85 percent of the U.S. baseline level, because emissions would continue from the CFC bank that already exists.

Economic incentives can provide a wide range of emissions reductions. While we have not analyzed the costs of reducing U.S. baseline emissions by more than about 30 percent, we do know that further reductions would cause costs to rise rapidly. However, economic incentives would be less costly than CFC bans in the middle range of emissions reductions, because incentives policies cause all less costly options to be tried before any application is eliminated. Consequently, the costs of economic incentives and equally effective CFC bans would become similar only near the maximum level of emissions reductions.

In summary, Fig. 6.1 shows that to achieve modest near-term reductions in U.S. emissions, the policy choice is between economic incentives and mandatory controls. For larger near-term emissions reductions, the choice is between economic incentives and CFC bans. Finally, even the most stringent restrictions on U.S. emissions can have only a modest payoff in ozone protection in the absence of regulatory action by other countries that contribute to worldwide emissions.

## CONTROLS VERSUS INCENTIVES

Suppose a goal is set for which both mandatory controls and economic incentives are effective. Figure 6.2 lists some of the factors that might influence the choice between the policies.

| Features | Controls | Incentives |
|---|---|---|
| Economic efficiency | | Greater in short and long run |
| Implementation | More familiar to EPA | |
| Enforcement | | Fewer sites to monitor |
| Transition | | Greater flexibility |
| Distributive effects | Lesser effects than uncompensated incentives | Lesser effects than controls when compensated |
| Risk tradeoffs | Less chemical substitution | |

Fig. 6.2—Comparison of features relevant to the choice between mandatory controls and equally effective economic incentives

Holding effectiveness constant, the economic efficiency of a policy is indicated by how low its compliance costs are. Compliance costs are lower under economic incentives, not only over the short run, when technical options are fixed, but also in the long run, because incentive policies induce innovations to achieve the desired goal in the most cost-effective manner.

By implementation, we mean the full set of activities involved in promulgating a regulation: dealing with legal challenges, collecting data, holding public hearings, and so on. Implementation under mandatory controls is somewhat simpler, because this type of policy mechanism is far more familiar to EPA. Taxes are not altogether unfamiliar policies, but they are not a common technique for environmental regulation, and their implementation is complicated by the probable need to obtain Congressional authority.

While implementation of mandatory controls is relatively straightforward, enforcement of the regulations is both costly and difficult because there are so many CFC user sites to be monitored. Economic incentives are easier to enforce, given the limited number of CFC production sites.[2]

Under mandatory controls, easing the industries' transition to regulation requires delays in implementing the regulations, thereby reducing their effectiveness. Under economic incentives, the same cumulative emissions reductions can be achieved by means of incentives that gradually increase over time.

Any type of regulation imposes more costs on some firms and consumers than on others; that is, regulation redistributes wealth. As Sec. V showed, the total losses to CFC-using industries as a group are smaller under mandatory controls than under economic incentives, unless, of course, transfer payments are compensated.

Finally, there may be somewhat lesser undesirable health or environmental side effects under mandatory controls, because they do not lead to as much chemical substitution as do economic incentives.

## TAXES VERSUS QUOTAS

If the policy decision is to use economic incentives, there is a choice between taxes and quotas. One major difference is in the nature of any discrepancies between actual and predicted outcomes. Given a demand curve like those estimated here, the two techniques yield the same outcomes. But if the estimated curve differs from the actual one—and we suspect that the actual curve may lie below the estimated one, as indicated in Fig. 6.3—a quota would increase CFC prices by less than we predict. The policy would still achieve the desired emissions reduction, but the cost per pound of reduction (for compliance and for transfer payments) would be less. In contrast a tax would lead to emissions reductions greater than predicted.

Equally effective uncompensated tax and quota policies generate equally large transfers of wealth away from user industries. However, uncompensated tax and quota policies can differ with respect to who receives the transfers. While the tax policies cause the payments to enter the general treasury for eventual redistribution throughout the economy, the destination of transfers caused by a quota policy depends on how the policy is implemented. If EPA sells permits under the quota, the transfers will be paid into the general treasury. However, if permits are not issued, or if they are directly allocated to the CFC producers, the producers will be the recipients of the transfers paid by CFC users.

## ADVANTAGES AND DISADVANTAGES OF COMPENSATION

Because an economic incentives policy can generate large transfer payments, the regulatory agency might want to engage in compensation. Designing a compensation scheme that does not distort the policy's incentives is not a simple matter operationally. Moreover, because such a scheme involves redistributing wealth

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[2] Economic incentives do, however, require effective enforcement of restrictions on CFC imports.

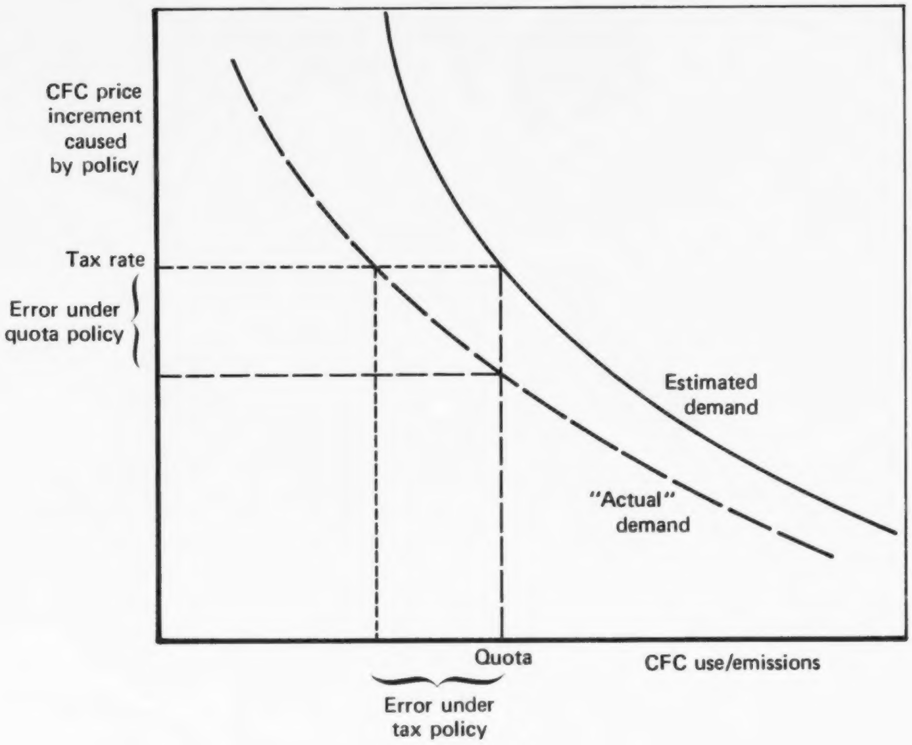
CFC price increment caused by policy
Tax rate
Error under quota policy
Estimated demand
"Actual" demand
Quota
CFC use/emissions
Error under tax policy

Fig. 6.3—Potential discrepancies between actual and estimated outcomes under taxes or quotas

among firms and industries, it is politically sensitive. But these disadvantages must be weighed against the fact that compensation can reduce consumer price and plant closure effects—which could be considerable under a stringent goal for emissions reduction. Moreover, even mandatory controls impose more costs on some firms and industries than on others, so compensation might be considered even under mandatory controls.

## CLOSING COMMENT

The CFC regulatory problem is an exceptionally complex one, spanning dozens of CFC applications in thousands of firms throughout the U.S. economy. If CFC depletion of the ozone layer warrants domestic regulation, several policy strategies —voluntary action, CFC bans, mandatory controls, and economic incentives—are available. This study has endeavored to measure the prospective effects of each policy along as many dimensions as possible.

Each policy has advantages and disadvantages. Voluntary action, while less costly to industry, promises to be relatively ineffective in reducing emissions over the next decade. CFC bans could effectively reduce near-term emissions, but would also impose excessive regulatory costs. Mandatory controls favorably compare with economic incentives along the dimensions of ease of implementation, costs borne by the CFC-using industries, and the risk tradeoffs inherent in CFC regulation. In contrast, economic incentives impose lower costs on the economy as a whole and offer far greater flexibility in both the timing and extent of emissions reductions. An incentives policy might seriously disrupt the CFC-using industries, depending on the magnitude of transfer payments; compensated economic incentives could mitigate transfer payments, but may be quite difficult to implement.

Clearly, no policy ranks first along all of the dimensions of policy comparison. Consequently, this study cannot—and does not—recommend a particular choice among the policy strategies. Ultimately, the choice will depend upon which dimensions of policy are deemed most important. That evaluation is left to the policymakers.

# Appendix A

# EFFECTS OF POLICY ACTION ON THE PRODUCTION OF PRECURSOR CHEMICALS[1]

The various policies that influence the use and emissions of the CFCs will also affect production of the precursor chemicals required for CFC manufacture. The significance of the impact depends both on the extent to which policy modifies the amount of CFC production and on the importance of the CFCs in the market for the precursor chemicals.

For reference purposes, Table A.1 reports the expected magnitude of the reductions in CFC production under the benchmark mandatory controls and under each of four economic incentive policy designs examined in Sec. IV. For a zero-growth scenario, the data in Table A.1 derive from the cautious demand assumptions (see Sec. IV). The overall reduction in use under a zero-growth policy is similar even when the alternative demand assumptions are used. However, the effects on use of individual CFCs are unknown for the alternative demand assumptions and therefore cannot be analyzed here.

The precursor chemicals for which CFC production comprises more than a trivial share of the precursor market are: hydrogen fluoride (HF); carbon tetrachloride ($CCl_4$); perchloroethylene ($C_2Cl_4$); chlorine ($Cl_2$); carbon disulfide ($CS_2$) and chloroform ($CHCl_3$). The effect of CFC regulation on production of these precursor chemicals is estimated below.

## METHOD OF ANALYSIS

Domestic CFC production differs from domestic CFC use according to the levels of exports and imports, packaging and distribution emissions, and the amounts of CFCs used to produce other chemicals. Historically, use has been a roughly constant proportion of production. To predict future production from projections of CFC nonaerosol use, we assume the same proportionality factor will hold through 1990, even under the regulatory scenarios. This method of analysis probably overstates the effects of regulation to a small degree because it assumes that net exports and the use of CFCs to make other chemicals would decline under regulation along with CFC domestic nonaerosol use.

We classify precursor chemicals into intermediate and preliminary precursors. Intermediate precursor chemicals are used directly to produce the CFCs, whereas preliminary precursor chemicals are used to produce the intermediate precursor chemicals. On the basis of the chemical equations for producing the CFCs and their precursors, and of the efficiencies of the production processes, we derive the factors

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[1] For a more extensive discussion of policy effects on the precursor chemicals—as well as on CFC production—see Wolf (1980).

Table A.1

REDUCTION IN CFC USE UNDER BENCHMARK CONTROLS AND FOUR ECONOMIC INCENTIVE POLICY DESIGNS
(Millions of pounds)

| | 1980 | | | | 1990 | | | |
|---|---|---|---|---|---|---|---|---|
| Policy design | CFC-11 | CFC-12 | CFC-113 | CFC-502 | CFC-11 | CFC-12 | CFC-113 | CFC-502 |
| Benchmark controls | 26.5 | 12.8 | 10.0 | -5.2 | 40.5 | 20.3 | 32.5 | -8.8 |
| Economic Incentives Policies That Achieve the Benchmark Reduction | | | | | | | | |
| Constant-price design | 19.9 | 7.5 | 24.3 | -5.2 | 30.3 | 11.9 | 49.3 | -8.8 |
| Cost-minimizing design | 19.9 | 7.5 | 6.5 | -5.2 | 37.5 | 17.6 | 56.1 | -8.8 |
| Economic Incentives Policies for Low and Zero Growth | | | | | | | | |
| Low growth | 0.0 | 0.0 | 6.0 | 0.0 | 57.8 | 36.4 | 79.3 | -8.8 |
| Zero growth[a] | 37.9 | 22.6 | 37.3 | -5.2 | 57.8 | 36.4 | 79.3 | -8.8 |

SOURCE: Calculations discussed in Sec. IV.

[a] Data derived from cautious assumptions (see Sec. IV).

listed in Tables A.2 and A.3. When multiplied by a given level of production of a particular chemical, a factor yields the amount of the precursor chemical required for the production process. Since $Cl_2$ is used both directly and indirectly in CFC production, it appears as both an intermediate and a preliminary precursor chemical.

## RESULTS

Table A.4 reports the baseline estimates of 1980 and 1990 production of the CFCs and their precursor chemicals.

Table A.5 estimates the reductions in precursor chemical production under five alternative regulatory policies examined in this report. For $CHCl_3$, all five policies yield an increase rather than a reduction in production, both in 1980 and 1990. The reason is that any of the five policies leads to an increase in the use of CFC-502, for which $CHCl_3$ is an important precursor. Under the low-growth economic incentive policy, 1980 production of HF is also greater under the regulation than for the baseline projections. The reason is that HF is used to produce CFC-502 and the increase in its use for that purpose initially offsets declines in its other uses under the policy.

Tables A.6 and A.7 together permit a crude assessment of the impact of CFC regulation on the precursor chemicals industry. Table A.6 shows the impact of CFC regulation on the portion of the precursor chemicals market that is generated by

## Table A.2

### INTERMEDIATE PRECURSOR CHEMICAL FACTORS

| Produced Chemical | Intermediate Precursor Chemical | Factor (pounds of the intermediate required to produce 1 lb of the CFC) |
|---|---|---|
| CFC-11 | $CCl_4$ | 1.14 |
| | HF | 0.15 |
| CFC-12 | $CCl_4$ | 1.30 |
| | HF | 0.34 |
| CFC-113 | $C_2Cl_4$ | 0.92 |
| | HF | 0.34 |
| | $Cl_2$ | 0.42 |
| CFC-502 | $C_2Cl_4$ | 0.57 |
| | HF | 0.58 |
| | $Cl_2$ | 0.25 |
| | $CHCl_3$ | 0.71 |

SOURCE: The factors were derived from information on the chemical equations and process efficiencies and were subsequently verified by industry sources.

## Table A.3

### PRELIMINARY PRECURSOR CHEMICAL FACTORS

| Produced Chemical | Preliminary Precursor Chemical | Factor (pounds of the preliminary precursor required to produce 1 lb of the produced chemical) |
|---|---|---|
| $CCl_4$ | $CS_2$ | 0.20 |
| | $Cl_2$ | 1.45 |
| $C_2Cl_4$ | $Cl_2$ | 0.81 |
| $CHCl_3$ | $Cl_2$ | 1.62 |

SOURCE: The factors were derived from information on the chemical equations and process efficiencies and were subsequently verified by industry sources.

## Table A.4

### BASELINE CFC AND PRECURSOR CHEMICAL PRODUCTION

(Millions of pounds)

| Chemical | 1980 | 1990 |
|---|---|---|
| CFC-11 | 144 | 262 |
| CFC-12 | 246 | 363 |
| CFC-113 | 87 | 147 |
| CFC-502 | 13 | 16 |
| HF | 141 | 221 |
| $CCl_4$ | 484 | 771 |
| $C_2Cl_4$ | 87 | 145 |
| $CHCl_3$ | 9 | 12 |
| $CS_2$ | 96 | 152 |
| $Cl_2$ | 825 | 1,317 |

SOURCE: CFC data taken from Tables 3.1 and 3.3. Precursor chemicals data derived as explained in text.

## Table A.5

### REDUCTION IN PRECURSOR CHEMICAL REQUIREMENTS, 1980 AND 1990[a]

(Millions of pounds)

| | 1980 | | | | | | 1990 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Policy design | HF | $CCl_4$ | $C_2Cl_4$ | $CHCl_3$ | $CS_2$ | $Cl_2$ | HF | $CCl_4$ | $C_2Cl_4$ | $CHCl_3$ | $CS_2$ | $Cl_2$ |
| Benchmark controls | 10 | 53 | 6 | -4 | 11 | 79 | 21 | 82 | 24 | -7 | 16 | 143 |
| Economic Incentives Policies That Achieve the Benchmark Reduction | | | | | | | | | | | | |
| Constant price design | 12 | 37 | 20 | -4 | 7 | 72 | 17 | 57 | 40 | -7 | 11 | 122 |
| Cost-minimizing design | 6 | 37 | 3 | -4 | 7 | 51 | 27 | 74 | 46 | -7 | 15 | 155 |
| Economic Incentives Policies for Low and Zero Growth | | | | | | | | | | | | |
| Low growth | -1 | 0 | 3 | -4 | 0 | -3 | 46 | 128 | 68 | -7 | 25 | 260 |
| Zero growth[b] | 25 | 82 | 33 | -4 | 16 | 154 | 46 | 128 | 68 | -7 | 25 | 260 |

[a] Calculations explained in text.

[b] Data derived from cautious assumptions. Overall use reductions are similar for the alternative demand assumptions, but distribution among CFCs is unknown (see Sec. IV).

## Table A.6

### PERCENT REDUCTION IN PRECURSOR CHEMICAL REQUIREMENTS FOR PRODUCING CFC-11, CFC-12, CFC-113, AND CFC-502[a]

(Millions of pounds)

| | 1980 | | | | | | 1990 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Policy design | HF | $CCl_4$ | $C_2Cl_4$ | $CHCl_3$ | $CS_2$ | $Cl_2$ | HF | $CCl_4$ | $C_2Cl_4$ | $CHCl_3$ | $CS_2$ | $Cl_2$ |
| Benchmark controls | 7 | 11 | 7 | -44 | 11 | 10 | 10 | 11 | 17 | -58 | 11 | 11 |
| Economic Incentives Designs That Achieve the Benchmark Reduction | | | | | | | | | | | | |
| Constant-price design | 9 | 8 | 23 | -44 | 7 | 9 | 8 | 7 | 28 | -58 | 7 | 9 |
| Cost-minimizing design | 4 | 8 | 3 | -44 | 7 | 6 | 12 | 10 | 32 | -58 | 10 | 12 |
| Economic Incentives Policies for Low and Zero Growth | | | | | | | | | | | | |
| Low growth | -1 | 0 | 3 | -44 | 0 | 0 | 21 | 17 | 47 | -58 | 16 | 20 |
| Zero growth | 18 | 17 | 38 | -44 | 17 | 19 | 21 | 17 | 47 | -58 | 16 | 20 |

[a] Calculations explained in text.

## Table A.7

### PRECURSOR CHEMICAL USAGE, 1976

(Millions of pounds)

| Usage Category | HF | $CCl_4$ | $C_2Cl_4$ | $CHCl_3$ | $CS_2$ | $Cl_2$ |
|---|---|---|---|---|---|---|
| CFC Manufacture | 295 | 803 | 103 | 247 | 159 | 1,690 |
| Aerosol | 98 | 401 | 29 | 0 | 79 | 616 |
| Nonaerosol | | | | | | |
| CFC-11<br>CFC-12<br>CFC-113<br>CFC-502 | 117 | 402 | 73 | 8 | 80 | 686 |
| Other | 80 | 0 | 1 | 239 | 0 | 388 |
| All other chemical processes | 346 | 54 | 569 | 45 | 477 | 17,310 |
| Total | 641 | 857 | 669 | 292 | 636 | 19,000 |

SOURCE: Total production of the chlorocarbons was taken from U.S. International Trade Commission (1976). Total production for the other chemicals was derived from data supplied by industry sources.

CFCs produced for nonaerosol applications. (The table shows the reductions from Table A.5 as a percentage of the production levels from Table A.4.) The data in Table A.7 indicate how important nonaerosol applications of CFCs were in the overall market for each precursor chemical in 1976, the most recent year for which overall precursor chemical market data are available.

In 1976, aerosol applications of CFCs generated a significant share of the market for each of the precursor chemicals except chloroform. This part of the precursor chemical market has now virtually disappeared in the wake of the aerosol ban. If the relative shares of the other markets for the precursor chemicals have remained stable, the CFCs that would come under the regulations examined in this study would today account for 22 percent of the HF market, 88 percent of the $CCl_4$ market, 11 percent of the $C_2Cl_4$ market, three percent of the $CHCl_3$ market, 14 percent of the $CS_2$ market, and four percent of the $Cl_2$ market. Hence, the $CHCl_3$ and $Cl_2$ markets are not very sensitive to effects of CFC regulation, and only the $CCl_4$ market could be described as critically dependent on CFC production levels.

It appears therefore, that the effects of CFC nonaerosol regulation would be quite modest in comparison with the effects of the aerosol ban. The largest impact of nonaerosol regulations would be felt in the $CCl_4$ market, where the reduction in total annual production might be as high as 10 percent. For other precursors, the effects of the nonaerosol CFC regulatory scenarios analyzed here would generally amount to less than a five percent reduction in the overall markets.

# Appendix B

# ESTIMATES OF FOOD FREEZING PRODUCTION COSTS

## Table B.1

### INDUSTRY-SUPPLIED ESTIMATES OF RELATIVE FOOD FREEZING COSTS, CIRCA 1978

| Conditions | Example A |  | Example B |  | Example C |  | Example D |  | Example E |  | Example F |  | Example G |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | LFF | Air Blast | LFF | Air Blast | LFF | $LN_2$ | LFF | $LN_2$ | LFF | $LN_2$ | LFF | $LN_2$ | LFF | $LN_2$ |
| Production rate (lb/hr) | 4,000 | 4,000 | 6,480 | 6,480 | 4,000 | 4,000 | 1,000 | 1,000 | 2,000 | 2,000 | 3,000 | 3,000 | 4,000 | 4,000 |
| Scheduled operation (hr/yr) | 4,000 | 4,000 | 4,000 | 4,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 |
| Annual production (millions of lb/yr) | 16.0 | 16.0 | 26.0 | 26.0 | 8 | 8 | 2 | 2 | 4 | 4 | 6 | 6 | 8 | 8 |
| Food type | Raw or cooked shrimp |  | Raw meat patties |  | Cooked pork patties |  | (unspecified) |  | (unspecified) |  | (unspecified) |  | (unspecified) |  |
| Investment-installed Equipment Cost ($) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Refrigerator | 155,000 | 155,000 | 170,000 | 170,000 | 185,000 | -- | 60,000 | -- | 100,000 | -- | 130,000 | -- | 165,000 | -- |
| Freezer | 249,000 | 190,000 | 320,000 | 380,000 | 215,000 | 85,000 | 110,000 | 50,000 | 120,000 | 60,000 | 140,000 | 70,000 | 165,000 | 80,000 |
| Total | 404,000 | 345,000 | 490,000 | 550,000 | 400,000 | 85,000 | 170,000 | 50,000 | 220,000 | 60,000 | 270,000 | 70,000 | 330,000 | 80,000 |
| Annual Operating Cost ($/yr) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Fixed cost |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Ownership | 73,000 | 62,000 | 88,000 | 99,000 | 100,000 | 21,000 | 31,000 | 9,000 | 40,000 | 11,000 | 49,000 | 13,000 | 59,000 | 14,000 |
| Maintenance | 4,000 | 3,500 | 4,900 | 5,500 | 8,000 | 1,000 | 7,000 | 8,000 | 9,000 | 9,000 | 11,000 | 11,000 | 13,000 | 12,000 |
| Freezant tank rental | -- | -- | -- | -- | -- | 10,000 | -- | 10,000 | -- | 10,000 | -- | 10,000 | -- | 10,000 |
| Total ($/yr) | 77,000 | 65,500 | 92,900 | 104,500 | 108,000 | 32,000 | 38,000 | 27,000 | 49,000 | 30,000 | 60,000 | 34,000 | 72,000 | 36,000 |
| Variable cost ($) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Power | 33,000 | 36,000 | 36,000 | 40,800 | 16,000 | 1,000 | 2,000 | -- | 4,000 | -- | 6,000 | -- | 8,000 | -- |
| Freezer labor | 20,000 | 20,000 | 10,000 | 10,000 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 |
| Gas cost ($/yr) | 188,000 | -- | 220,000 | -- | 108,000 | 440,000 | 40,000 | 160,000 | 62,000 | 216,000 | 65,000 | 306,000 | 79,000 | 320,000 |
| (gas use rate lb/lb) | (0.025) | -- | (0.018) | -- | (0.03) | (2.0) | (0.035) | (2.0) | (0.027) | (1.8) | (0.024) | (1.7) | (0.022) | (1.6) |
| (gas cost $/lb) | (0.47) | -- | (0.47) | -- | (0.45) | (0.0275) | (0.57) | (0.04) | (0.57) | (0.03) | (0.45) | (0.03) | (0.45) | (0.025) |
| Yield loss (%) | (0.25) | (1.5) | (0.25) | (0.6) | (Yield loss not included in these illustrations) |  |  |  |  |  |  |  |  |  |
| ($/yr) | 160,000 | 960,000 | 39,000 | 93,600 |  |  |  |  |  |  |  |  |  |  |
| Throughput charge | -- | -- | -- | -- | 8,000 | -- | 2,000 | -- | 4,000 | -- | 6,000 | -- | 8,000 | -- |
| Total | 401,000 | 1,016,000 | 305,000 | 144,400 | 137,000 | 446,000 | 49,000 | 165,000 | 75,000 | 221,000 | 82,000 | 331,000 | 100,000 | 325,000 |
| Total Annual Operating Cost ($/yr) | 478,000 | 1,081,500 | 397,900 | 248,900 | 245,000 | 478,000 | 87,000 | 192,000 | 124,000 | 251,000 | 142,000 | 345,000 | 172,000 | 361,000 |
| Unit Operating Cost (¢/lb) | 2.98 | 6.76 | 1.53 | 0.96 | 3.06 | 5.98 | 4.35 | 9.60 | 3.10 | 6.28 | 2.37 | 5.75 | 2.15 | 4.51 |

SOURCE: Examples obtained from industry sources, not necessarily representing actual operating conditions.

NOTES: Examples A and B: Calculations assume a seven-year required payback period, maintenance at 1 percent of ownership costs, power priced at \$0.03/kWh, freezer labor at \$5/hr and yield loss at \$4/lb for Example A and at 60¢/lb in Example B. Example C: Calculations assume a four-year required payback period, maintenance at 2 percent of ownership costs for LFF and 1 percent for $LN_2$, power priced at \$0.03/kWh, and freezer labor at \$5/hr. The "throughput charge" represents payments for a portion of capital costs. If all capital costs were paid up front, the throughput charge would be zero and the initial purchase price would be increased by about \$50,000. Examples D through G: Calculations assume a seven-year required payback period, maintenance at 4 percent of ownership costs for LFF and at 15 percent for $LN_2$, power priced at \$0.015/kWh, and freezer labor at \$5/hr. The "throughput charge" is a part of capital costs but paid over time (see note for Example C).

# Appendix C

# POINT ESTIMATES OF 1980 AND 1990 CFC DEMAND SCHEDULES

### Table C.1

### DEMAND SCHEDULES FOR FULLY HALOGENATED CFCs BY TYPE OF CFC, 1980 AND 1990

| CFC-11 | | CFC-12 | | CFC-113 | |
|---|---|---|---|---|---|
| Price Increment (1976 $ per lb) | CFC Use (millions of lb) | Price Increment (1976 $ per lb) | CFC Use (millions of lb) | Price Increment[a] (1976 $ per lb) | CFC Use (millions of lb) |
| 1980 | | | | | |
| 0.00 | 130.8 | 0.00 | 188.7 | 0.00 | 78.3 |
| 0.10 | 118.2 | 0.19 | 183.5 | 0.22 | 71.8 |
| 0.27 | 116.2 | 0.24 | 181.2 | 0.35 | 58.3 |
| 0.34 | 110.9 | 0.58 | 177.6 | 0.57 | 53.7 |
| 0.70 | 107.2 | 1.02 | 175.8 | 1.27 | 45.6 |
| 0.79 | 106.2 | 1.23 | 174.0 | 2.03 | 41.0 |
| 1.16 | 98.2 | 1.32 | 170.4 | | |
| 1.18 | 92.9 | 1.36 | 168.6 | | |
| | | 1.59 | 166.1 | | |
| 1990 | | | | | |
| 0.00 | 252.2 | 0.00 | 279.8 | 0.00 | 147.1 |
| 0.10 | 233.0 | 0.19 | 271.1 | 0.15 | 121.2 |
| 0.27 | 229.9 | 0.24 | 267.9 | 0.35 | 120.4 |
| 0.34 | 221.9 | 0.58 | 262.2 | 0.50 | 97.8 |
| 0.70 | 216.2 | 1.02 | 259.4 | 0.73 | 90.0 |
| 0.79 | 214.7 | 1.23 | 256.6 | 1.43 | 75.6 |
| 1.16 | 202.4 | 1.32 | 250.9 | 2.20 | 67.8 |
| 1.18 | 194.4 | 1.36 | 248.1 | | |
| | | 1.59 | 243.4 | | |

SOURCE: Based on detailed calculations discussed in Secs. III.A. through III.H.

[a] Indicates price increment above supply price. The supply price for CFC-113 declines as production increases.

## Table C.2

## DEMAND SCHEDULE FOR CFCs, AGGREGATE 1980 AND 1990

| 1980 | | | 1990 | | |
|---|---|---|---|---|---|
| Price Increment[a] (1976 $ per permit pound[b]) | Product Area of Induced Activity | Total CFC Use (millions of permit pounds[b]) | Price Increment[a] (1976 $ per permit pound[b]) | Product Area of Induced Activity | Total CFC Use (millions of permit pounds[b]) |
| 0.00 | -- | 454.9 | 0.00 | -- | 784.4 |
| 0.07 | Flexible foam | 431.7 | 0.07 | Flexible foam | 747.4 |
| 0.18 | Retail food | 427.6 | 0.15 | Solvents | 732.3 |
| 0.20 | Flexible foam | 424.8 | 0.18 | Retail food | 725.4 |
| 0.22 | Solvents | 424.3 | 0.20 | Flexible foam | 721.3 |
| 0.23 | Retail food, PS sheet | 421.9 | 0.23 | Retail food, PS sheet | 717.9 |
| 0.25 | Flexible foam | 414.7 | 0.25 | Flexible foam | 707.0 |
| 0.35 | Solvents | 401.2 | 0.35 | Solvents | 706.2 |
| 0.51 | Flexible foam | 396.2 | 0.50 | Solvents | 683.6 |
| 0.56 | PS sheet | 392.4 | 0.51 | Flexible foam | 675.8 |
| 0.57 | Solvents | 387.8 | 0.56 | PS sheet | 669.9 |
| 0.58 | Flexible foam | 386.4 | 0.58 | Flexible foam | 667.9 |
| 0.85 | Flexible foam | 375.5 | 0.73 | Solvents | 660.1 |
| 0.87 | Flexible foam | 368.2 | 0.85 | Flexible foam | 643.3 |
| 0.99 | PS sheet | 366.4 | 0.87 | Flexible foam | 632.4 |
| 1.19 | PS sheet | 364.4 | 0.99 | PS sheet | 629.5 |
| 1.27 | Solvents | 356.3 | 1.19 | PS sheet | 626.4 |
| 1.28 | PS sheet | 352.6 | 1.28 | PS sheet | 620.5 |
| 1.32 | PS sheet | 350.7 | 1.32 | PS sheet | 617.6 |
| 1.54 | Mobile air conditioning | 348.1 | 1.43 | Solvents | 603.2 |
| 2.03 | Solvents | 343.5 | 1.54 | Mobile air conditioning | 598.3 |
| | | | 2.20 | Solvents | 590.5 |

SOURCE: Based on detailed calculations discussed in Secs. III.A through III.H. Estimates include demand for CFC-11, CFC-12, and CFC-113, and demand for CFC-502 in retail food refrigeration only.

[a] Indicates price increment above supply price. The supply price for CFC-113 declines as production increases as a result of economies of scale.

[b] One permit pound is equivalent to 1.00 pound of CFC-113, 0.97 pound of CFC-12, 0.73 pound of CFC-11, or 3.87 pounds of CFC-502. See Sec. IV for discussion.

# Appendix D

# ESTIMATION OF CFC DEMAND SCHEDULES FOR PLASTIC FOAMS

This appendix details the procedure employed to estimate CFC demand schedules for flexible urethane foam and thermoformed extruded polystyrene sheet foam. Because data are unavailable for the direct econometric estimation of the demand schedules in these markets, estimates are based on technical cost data for alternative foam production processes.

The demand analysis is predicated on the assumption that foam producers seek to use the least costly method of production. The estimation procedure involves two steps. First, production costs are estimated for each technical option that might be adopted by foam producers at higher CFC prices. Because the costs of these alternative production processes differ in their sensitivity to higher CFC prices and involve different levels of initial capital outlays, the least costly option for a firm depends upon the expected CFC price. The second step simply involves determining which option minimizes production costs, *given* the regulated price at which the relevant CFC is expected to stabilize.

When confronted with higher CFC prices, the possible responses of foam producers include:

1. Pay the higher CFC price.
2. Recover and recycle CFC.
3. Convert to alternative blowing agents.
4. Convert to alternative blowing agents where feasible, and recover both CFC and the alternative blowing agent.[1]

Because the adoption of any of these options is unlikely to affect significantly a foam producer's costs of labor, capital, and other nonmaterial inputs, the demand analysis focuses on material costs. For the responses listed above, annual material costs are described in Eqs. (D.1) to (D.4), respectively. (Table D.1 contains the definitions of all variables.)

$$TC_1 = [p_cC + p_mM] \tag{D.1}$$

$$TC_2 = [p_c(1 - e)C + beC + p_mM + O_r] + \lambda K_r \tag{D.2}$$

$$TC_3 = [(p_cC + p_mM)f + (p_aA + p_mM)(1 - f)\alpha + O_a] + \lambda K_a \tag{D.3}$$

$$\begin{aligned} TC_4 = {} & [(p_c(1 - e)C + beC + p_mM)f + (p_a(1 - e)A + beA \\ & + p_mM)(1 - f)\alpha + O_r + O_a] + \lambda(K_r + K_a) \end{aligned} \tag{D.4}$$

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[1] Note that this last option is relevant only for flexible urethane foam producers. A fifth option is to shut down the production facility. While this possibility is not discussed in this appendix, it may be relevant for some polystyrene sheet producers, as emphasized in Sec. III.C.

## Table D.1

### VARIABLE DEFINITIONS FOR ESTIMATING CFC DEMAND SCHEDULES IN PLASTIC FOAM MARKETS

| Variable | Definition |
|---|---|
| $TC_i$ | Materials cost of ith option (i = 1, ..., 4) |
| $p_c$ | CFC price |
| $p_a$ | Price of alternative blowing agent |
| $p_m$ | Price of nonblowing agent materials |
| C | Quantity of CFC use |
| A | Quantity of alternative blowing agent |
| M | Quantity of nonblowing agent materials |
| $K_r$ | Initial capital costs for CFC recovery |
| $K_a$ | Initial capital costs for conversion to alternative blowing agent |
| $O_r$ | Other annual costs for CFC recovery[a] |
| $O_a$ | Other annual costs for conversion to alternative blowing agent[a] |
| $\lambda$ | Discount factor |
| e | Fraction of CFC reused under CFC recovery |
| b | Operating cost of CFC recovery unit per pound of recovered CFC |
| $\alpha$ | Material cost adjustment factor of conversion to alternative blowing agent ($\alpha \geq 1.0$) |
| f | Fraction of CFC use that technically cannot be converted to alternative blowing agent |

[a] Includes insurance, additional labor, and other costs. See Secs. III.A and III.C. for a discussion of these variables.

In Eqs. (D.1) to (D.4) the bracketed terms describe the cost of materials plus annual labor and insurance costs associated with CFC recovery or conversion to an alternative blowing agent. The unbracketed terms, $\lambda K_r$, $\lambda K_a$, and $\lambda(K_r + K_a)$, refer to the amortized capital expenses for each option, where $\lambda$ is a discount factor determined by the investment criteria of the firm.

As an illustration, consider the alternative costs of production for a large flexible urethane slabstock plant that primarily produces softer foam products. In this case, the alternative blowing agent is methylene chloride, which can be used to produce all but 25 percent of a slabstock producer's output on average (i.e., $f = 0.25$). Moreover, the use of this chemical may result in higher levels of rejected product (or scrap). This phenomenon is reflected in the value of $\alpha$, which in this case equals 1.125. The discount factor, $\lambda$, is based on a 10 year average life for equipment and 20 percent pretax annual opportunity cost of capital (or, equivalently, a 4.2 year payback period requirement). Because 15 percent less methylene chloride than

CFC is required to produce a given amount of foam (ignoring scrap), we also have $A = 0.85C$. Finally, available evidence indicates that at the current CFC price of \$0.34 per pound, CFC accounts for about 13 percent of total material costs for soft flexible slabstock foam; this implies the cost of nonblowing agent materials is $p_mM = (0.34C/0.13)\ 0.87$.

On the basis of these observations and the data presented in Sec. III.A for flexible slabstock, we have the following parameters for Eqs. (D.1) to (D.4):

$$\begin{array}{ll} p_a = \$0.22 & \lambda = 0.24 \\ K_r = \$960{,}000 & e = 0.5 \\ K_a = 0 & b = 0.014 \\ O_r = \$26{,}800 & \alpha = 1.125 \\ O_a = 0 & f = 0.25 \\ A = 0.85C & P_mM = 2.28C \end{array}$$

Substituting these values into Eqs. (D.1) to (D.4), total material costs (in millions of 1976 dollars) for a flexible urethane foam producer are:

$$TC_1 = (p_c + 2.28)C \qquad \text{(D.1a)}$$

$$TC_2 = (0.5\ p_c + 2.29)C + 0.256 \qquad \text{(D.2a)}$$

$$TC_3 = (0.25\ p_c + 2.65)C \qquad \text{(D.3a)}$$

$$TC_4 = (0.13\ p_c + 2.58)C + 0.256 \qquad \text{(D.4a)}$$

Equations (D.1a) to (D.4a) describe material costs under each respective option as a function of the CFC price and the amount of CFC the firm would use in the absence of regulation. Figure D.1 illustrates these annual material cost curves for a large flexible slabstock plant, where the value of C is 1.2 million pounds per year (see Table 3.A.5).

The kinked bold line at the bottom of the figure shows which option is characterized by the lowest material costs over several ranges of the price of CFC-11. Not surprisingly, at CFC-11 prices near the current level (\$0.34 per pound in 1976 dollars), the most profitable action for the firm is simply to pay the higher price. However, material costs rise rapidly under this option as the price of CFC is increased by regulation.[2] If the regulated price is between \$0.44 and \$0.61, the least cost response of the firm is CFC recovery. While CFC recovery requires a large initial investment, this cost is more than offset by the savings realized by the firm, because it purchases less CFC blowing agent. Similarly, if the regulated CFC-11 price is between \$0.61 and \$1.13 per pound, the firm's most profitable course of action is to convert to methylene chloride. Above the price of \$1.13 per pound, the firm further reduces its use of CFC by converting to methylene chloride for the products that can be produced with this chemical and using recovery equipment to reuse both CFC and methylene chloride.[3]

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[2] That is, the slope of $TC_1$ is greater than the slope of the other cost functions.

[3] The permit prices in a permit market or tax rate per permit pound corresponding to the CFC-11 prices in Fig. D.1 are as follows:

| CFC-11 Price per Pound | Corresponding Price Increment per Permit Pound |
|---|---|
| \$0.44 | \$0.07 |
| \$0.61 | \$0.20 |
| \$1.13 | \$0.58 |

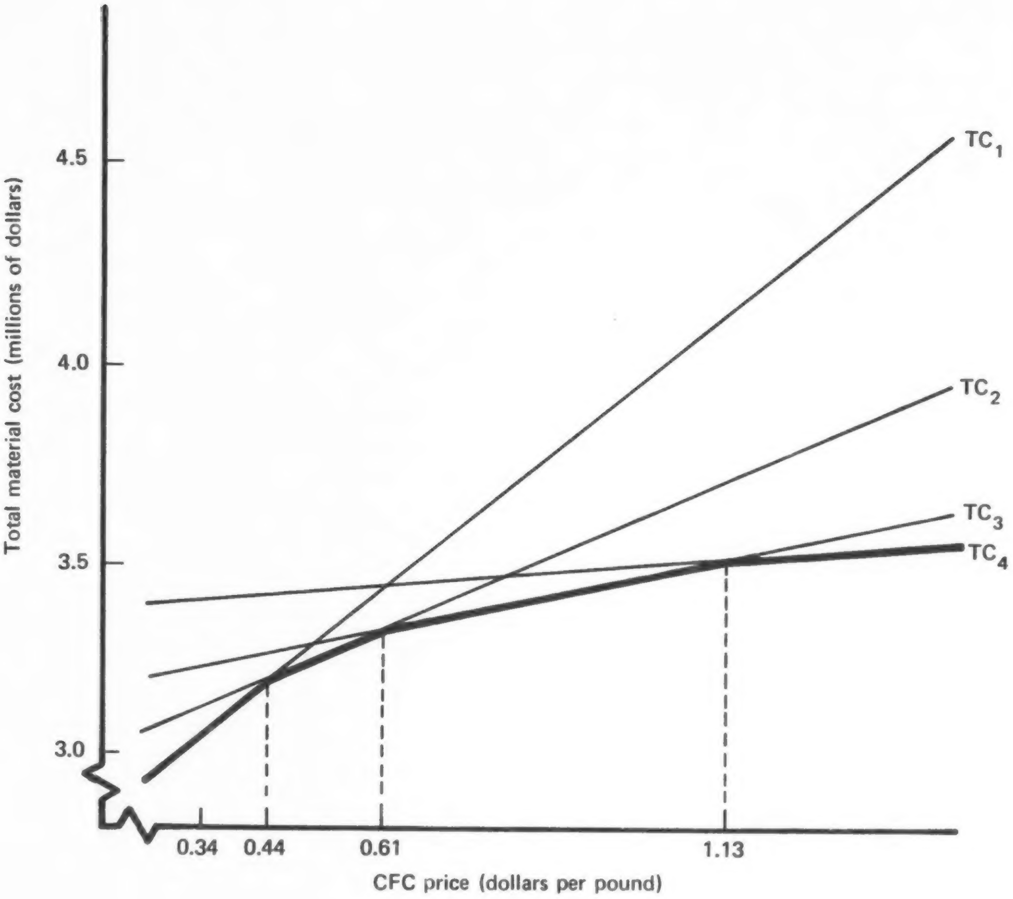

Fig. D.1—Annual material costs for a large flexible slabstock plant

# Appendix E

# THE SOLVENTS SIMULATION MODEL

Table E.1 lists the assumed characteristics of the stock of solvent-using equipment for cleaning and drying applications of CFC-113. Each of eight cases is defined by a representative set of characteristics that are presumed to yield averages for the vapor and waste losses per machine. Individual machines might differ somewhat from the case characteristics.

The descriptions of the unit types were based on an examination of brochures from the major equipment manufacturers. The descriptions were checked with the CFC-113 producers who agreed that these eight types of units fairly well represent the major categories of equipment in use, and who provided estimates of the distribution of the equipment stock among the eight cases. (See the last column of Table E.1.) For each unit type, the estimates of total capacity, surface area, and boil sump capacity were also derived from equipment brochures. Individuals at DuPont and Allied Chemical who are familiar with field uses of CFC-113 contributed to the work hours and shifts estimates.

Most industry sources cite 0.5 as the most common rate of vapor loss (in pounds) per square foot of surface area during use of a machine for cleaning throughput.[1] However, it is also recognized that small spray units are relatively inefficient, while conveyorized units are relatively efficient at controlling CFC losses. These differences among equipment units are reflected in the work loss rates shown in Table E.1. Similarly, there are some differences in the idle loss rates, when equipment is turned on but is not being used. Industry sources generally agree that covers are used during about one-quarter of all idle time; of course, conveyorized units do not use covers because the units are enclosed.

The equipment manufacturers and the CFC-113 producers recommend that equipment be cleaned out when the contamination in the boil sump reaches 10 percent of boil sump capacity. Because units with more sumps can be run somewhat longer between cleanings, and because small spray units are not often used for highly delicate cleaning operations, we assume that the units in cases 1, 3, and 5 are operated to 15 or 20 percent contamination before cleaning. Many users put the waste from the cleaned unit back through the equipment unit, using it as a crude still. Then virgin CFC is added and the solvent continues to be used until clean-out is again necessary. As a result, the effective contamination limit that determines when the waste will require precision reclamation or will be sent out for disposal is far greater than 10 percent. The contamination limits shown in Table E.1 refer to this effective level of contamination at which waste requiring precision reclamation or burial is generated.

The contamination rate in the table refers to the rate at which contamination

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[1] The simulations are based on information about cleaning applications; drying applications are relatively uncommon at present, and are assumed to be similar to cleaning applications in emissions properties.

## Table E.1

## POSTULATED CHARACTERISTICS OF THE CURRENT EQUIPMENT STOCK FOR CLEANING AND DRYING APPLICATIONS[a]

| Case Number | Unit Type | Capacity (gallons) | Surface (sq. ft) | Boil-Sump Capacity (gallons) | Work Hours per shift | Shifts per Day | Work Loss Rate[b] | Idle Loss Rate[b] |  | Contamination |  | Share of Equipment Stock |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  | Covered | Uncovered | Rate (lb/work hour) | Limit[c] (%) |  |
|  | Small |  |  |  |  |  |  |  |  |  |  |  |
| 1 | Spray | 5 | 2 | 3.5 | 2.0 | 1.0 | 0.60 | 0.04 | 0.20 | 0.11 | 20 | 0.16 |
| 2 | One-sump | 15 | 2 | 10.5 | 3.0 | 1.2 | 0.50 | 0.04 | 0.20 | 0.15 | 20 | 0.32 |
| 3 | Two-sump | 15 | 2 | 6.0 | 3.0 | 1.5 | 0.50 | 0.04 | 0.20 | 0.15 | 30 | 0.32 |
|  | Medium |  |  |  |  |  |  |  |  |  |  |  |
| 4 | One-sump | 60 | 6 | 42.0 | 4.0 | 1.5 | 0.50 | 0.04 | 0.10 | 0.20 | 30 | 0.04 |
| 5 | Two-sump | 60 | 6 | 24.0 | 5.0 | 1.6 | 0.50 | 0.04 | 0.10 | 0.20 | 30 | 0.09 |
| 6 | Conveyor | 60 | 6 | 18.0 | 5.5 | 1.8 | 0.30 | 0.05 | N/A | 0.20 | 30 | 0.04 |
|  | Large |  |  |  |  |  |  |  |  |  |  |  |
| 7 | One/two-sump | 375 | 25 | 188.0 | 6.0 | 2.0 | 0.50 | 0.04 | 0.10 | 0.20 | 30 | 0.01 |
| 8 | Conveyor | 375 | 25 | 150.0 | 7.0 | 2.0 | 0.30 | 0.05 | N/A | 0.20 | 30 | 0.02 |

[a] Calculations explained in text.

[b] In pounds per square foot of surface area per hour.

[c] Percent contamination in the boil sump (after boil-down) at which waste is removed for external recovery or recycle.

displaces solvent in the boil sump during work hours. The contamination rate for case 3 was inferred from a detailed case analysis provided by DuPont; the rates for other cases were adjusted from the case 3 estimate, on the basis of judgments (our own and those of individuals at Allied Chemical) about differences in the types of applications for which different types of equipment are used.

A characteristic of equipment in use that is not reported in Table E.1 is the shutdown loss rate—the rate of vapor losses when equipment is turned off, mostly overnight and on weekends.[2] The two CFC-113 producers disagree sharply on shutdown loss rates. One argues that equipment is covered during shutdown about 75 percent of the time, and that loss rates then are 0.02 lb/sq. ft/hour, whereas loss rates when equipment is uncovered are 0.10. The other producer claims that equipment is always covered when shut down, but that the shutdown loss rate is 0.08 lb/sq. ft/hour. The latter assumption nearly doubles the estimates of shutdown losses for all machines, and suggests that there is a considerable amount of vapor loss that cannot be reduced through better operating practices or even by equipment improvements that do not include a redesign of covers for machines. Both shutdown loss assumptions are examined in more detail below.

In recent years, CFC-113 accounted for 89.7 percent of the total number of pounds of CFC-based solvent sales. Using 11.85 as the average density of azeotropes and 13.06 as the density of pure CFC-113, the average amount of CFC-113 used per gallon of equipment capacity is 11.17 pounds. Using this conversion factor and the assumptions from Table E.1, the normal losses of CFC-113 per machine per year would be as shown in Table E.2.

There are two reasons to suspect that the "high" shutdown loss assumption is the more accurate one. First, the turnover rates in Table E.2 for the high shutdown loss assumption are closer to the turnover rates estimated by the CFC-113 producers (before they saw the results of the simulation model). Second, when the simulation model is combined with an estimate that there were about 11,000 units in the 1976 equipment stock, the results for the high shutdown loss assumption come far closer to explaining total CFC-113 sales for cleaning and drying applications in that year.[3] Nevertheless, for lack of hard data on shutdown losses, our analysis assumes that losses are halfway between the high and low estimates.

## EFFECTS OF IMPROVED CONSERVATION

We have been able to find no data concerning the decrease in vapor losses from equipment improvements under actual operating conditions. Industry sources cite emissions reductions of 40 to 60 percent from replacing or modifying a poorly designed machine, but they also argue that many CFC-113 users already use fairly well designed equipment, because the cost of the CFC solvent warrants good conservation.

In the simulation model, we assume that equipment improvements can reduce the work loss rate in all cases to 0.03 lb/sq. ft/hour; can reduce the idle loss rate

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[2] Shutdown hours per year are 6,744 for all cases.

[3] That is, after taking account of external reclamation amounting to about three or four percent of virgin CFC sales.

## Table E.2

### Normal Annual Losses per Machine[a]

(Pounds of CFC-113)

| Case Number | Unit Type[b] | Vapor Loss |  |  |  | Waste Loss | Total Loss | Turnover Rate (fills per year) |
|---|---|---|---|---|---|---|---|---|
|  |  | Work | Idle | Shutdown | Total |  |  |  |
| "Low" Shutdown Loss Assumption |  |  |  |  |  |  |  |  |
| 1 | Spray | 543 | 434 | 485 | 1,462 | 194 | 1,656 | 33.0 |
| 2 | Small (I) | 814 | 434 | 455 | 1,703 | 971 | 2,674 | 17.8 |
| 3 | Small (II) | 1,017 | 543 | 412 | 1,972 | 704 | 2,676 | 17.8 |
| 4 | Medium (I) | 4,070 | 692 | 1,236 | 5,998 | 1,869 | 7,867 | 13.1 |
| 5 | Medium (II) | 5,427 | 1,182 | 1,192 | 7,801 | 1,670 | 9,471 | 15.8 |
| 6 | Medium (C) | 4,030 | 305 | 1,105 | 5,440 | 3,058 | 8,498 | 14.2 |
| 7 | Large (I/II) | 20,350 | 961 | 4,242 | 25,553 | 3,802 | 29,355 | 7.8 |
| 8 | Large (C) | 23,742 | 565 | 4,242 | 28,549 | 4,369 | 32,998 | 8.7 |
| "High" Shutdown Loss Assumption |  |  |  |  |  |  |  |  |
| 1 | Spray | 543 | 434 | 968 | 1,945 | 194 | 2,139 | 42.7 |
| 2 | Small (I) | 814 | 434 | 911 | 2,159 | 971 | 3,130 | 20.8 |
| 3 | Small (II) | 1,017 | 543 | 824 | 2,384 | 704 | 3,088 | 20.6 |
| 4 | Medium (I) | 4,070 | 692 | 2,460 | 7,222 | 1,869 | 9,091 | 15.1 |
| 5 | Medium (II) | 5,427 | 1,182 | 2,373 | 8,982 | 1,670 | 10,652 | 17.7 |
| 6 | Medium (C) | 4,030 | 305 | 2,199 | 6,534 | 3,058 | 9,592 | 15.9 |
| 7 | Large (I/II) | 20,350 | 961 | 8,484 | 29,795 | 3,802 | 33,597 | 8.9 |
| 8 | Large (C) | 23,742 | 565 | 8,484 | 32,791 | 4,369 | 37,160 | 9.9 |

[a] Calculations explained in text.

[b] I = one-sump, II = two-sump, C = conveyor.

to 0.04 lb/sq. ft/hour; and can reduce the shutdown loss rate to 0.02 lb/sq. ft/hour. The reduction in vapor losses for each of the simulation cases is shown in Table E.3, both in pounds per year and as a percentage of total vapor losses. Averaging over the eight cases (weighted by their shares of the total equipment stock), the improvements reduce annual vapor losses by 45 percent. However, as a fraction of total losses per machine (both vapor and waste), the improvements reduce CFC-113 use by just 25 percent. This estimate, which appears to us to depend on a rather optimistic view of what improvements in equipment design can achieve, is nevertheless substantially below the 40 to 60 percent improvement figures so often cited.

## EFFECTS OF INCREASED RECLAMATION

The CFC-113 producers estimate that outside reclamation amounted to perhaps four percent of solvent sales for cleaning applications in 1976. Given virgin cleaning and drying sales of 55 million pounds, this implies that about 2.4 million pounds were reclaimed, and a 90 percent reclamation yield rate implies that 2.2 million pounds actually reentered use after reclamation.

According to the chemical reclaimers we interviewed, reclamation is far more common among users of large units, like those in cases 7 and 8. We assume that

Table E.3

ESTIMATED ANNUAL CONSERVATION POTENTIAL FROM EQUIPMENT IMPROVEMENTS[a]

| Case Number | Reduction in Vapor Losses (pounds per machine) | Reduction as Fraction of Normal Vapor Loss[b] (%) |
|---|---|---|
| 1 | 1,084 | 64 |
| 2 | 1,108 | 57 |
| 3 | 1,228 | 56 |
| 4 | 3,118 | 49 |
| 5 | 4,280 | 51 |
| 6 | 1,161 | 19 |
| 7 | 12,891 | 47 |
| 8 | 4,355 | 14 |

[a] Calculations explained in text.

[b] "Normal" assumes shutdown losses are halfway between the lower and upper estimates in Table E.2.

they already reclaimed about 80 percent of their waste in 1976, accounting for 0.77 million pounds of reclaimed CFC. We also assume that small users (cases 1, 2, and 3) do not reclaim currently. This implies that, on average, users in cases 4, 5, and 6 already reclaim about 30 percent of their waste.

At current CFC prices, mandatory controls requiring more reclamation of waste do not appear enforceable. Most users already reclaim in-house as much as possible, and outside reclamation is costly (at over 30 cents per pound, plus handling, storage, and transportation costs).

However, if the virgin CFC price were to rise to as much as a dollar per pound (1976 dollars), we do expect some improvements in reclamation activity. Specifically, our simulation assumes that the average share of waste sent for reclamation would rise to almost 75 percent (70 percent in cases 1, 2, and 3; 80 percent in cases 4, 5, and 6; and 90 percent in cases 7 and 8).

## THE CFC DEMAND SIMULATION

The assumed equipment prices for conservative and less conservative equipment for all eight simulation cases were presented in Sec. III.B. Here we work through the demand model for a single example. Case 3 is used, both because it is one of the predominant cases in the current equipment stock and because behavior in that case exemplifies most of the features of the economic analysis.

Consider a CFC user who is contemplating a purchase of new equipment in case 3. The estimated price of a conservative machine is $7,800. Assuming an average equipment life of eight years and an opportunity cost of capital of 20 percent, the average annual cost of the machine would be $2,028. In contrast, a less conservative machine might be priced 40 percent lower, at $4,680, having an annualized cost of

$1,217. The more conservative machine would reduce annual vapor losses (and, hence, annual CFC-113 purchases) by 1,228 pounds. Consequently, the CFC-113 price at which the more conservative machine would generate solvent savings sufficient to offset the higher machine cost is only about 66 cents. Since the 1980 price of CFC-113 (in 1976 dollars) is approximately 60 cents, we assume all new users in case 3 would buy the more conservative machine if the CFC-113 price rose by six cents (in real terms).

If the CFC-113 price were higher than 60 cents in 1980, there might be an additional demand effect over and above the inducement to improve equipment. The higher price might induce users to convert to another solvent. If the cost of converting equipment is 40 percent as much as the cost of buying new (conservative) equipment, then the conversion cost in case 3 would be $3,120, or $811 per year. We assume that at 60 cents per pound of CFC, some case 3 CFC users are close to indifferent about the choice to use either CFC or an alternative solvent, implying that for them the cost of using the alternative solvent is $2,946 per year.[4] Adding in the annualized conversion cost, the annualized cost of converting to a different solvent would be $3,757. With less conservative equipment, the annualized cost of using the CFC (including equipment costs) would not make conversion attractive unless the CFC price rose to at least 88 cents per pound. However, the user can choose the option of making his equipment more conservative, and at a price of 88 cents, the annualized cost of continuing to use the CFC would then be only $3,483, and the user would still not find it attractive to convert to another solvent. With the more conservative equipment, the user would not be interested in converting unless the CFC price rose to $1.04 per pound. However, at $1.00, the user would find it cost-saving to reclaim some waste, at an implicit price of $1.00 per pound of reclaimed material. With reclamation (at about 400 pounds per year), the cost of continuing to use the CFC (in conservative equipment) is only $3,732 at a CFC price of $1.04—still not high enough to induce conversion away from the CFC.

Finally, at CFC prices just a little higher, the user who was close to indifferent between the CFC and an alternative solvent when the CFC price was 60 cents will begin to find conversion attractive. Assuming that one percent of use will be converted to a different solvent for each one percent increase in the total cost of using the CFC above the alternative's cost ($3,757), a price for the CFC of $2.00 per pound, for example, would reduce CFC use in case 3 by about 30 percent (relative to what use would be with good conservation and reclamation.)

The same sort of analysis is performed for other equipment types and used to generate the overall demand results shown in Sec. III.B.

## EFFECTS OF MANDATORY CONTROLS

Again using case 3 as an example, we calculate the compliance cost for equipment standards by using the data on equipment costs. In 1990, the price difference between conservative and nonconservative equipment is assumed to be the same (in 1976 dollars) as in 1980: $811 per year (annualized). The baseline 1990 CFC-113 price is expected to be 40 cents.[5] Consequently, the more conserving equipment would save the user only $491 dollars per year in reduced solvent expenditure. Net of this solvent saving, the user is incurring $320 in extra production costs for 1990 due to the requirement that he use better equipment. The total number of case 3 machines in 1990 is projected to be 8,173, implying that total 1990 compliance costs for case 3 users would be $2.6 million. Adding in the costs for other years and discounting by 11 percent per year beyond 1980, the cumulative compliance costs for this case come to the $6.6 million figure shown in Table 3.B.12.

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[4] At 60 cents for the CFC, the annual cost of using it is the annualized cost of less conservative equipment ($1,217) plus the cost of the solvent (2,882 pounds per year in the less conservative machine).

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[5] Under mandatory controls, the 1990 CFC-113 price is expected to decline to only 45 cents. However, if 40 cents is the long-run marginal cost of producing CFC-113 and 45 cents is the short-run marginal cost, then the 45 cents that users would pay would be five cents above the long-run cost of production, and this five cent discrepancy is an additional real resource cost imposed by the mandatory controls. Hence, the use of the 40 cent figure in calculating the compliance cost for 1990.

# Appendix F

# A SIMULATION MODEL OF CHLOROFLUOROCARBON EMISSIONS FROM CLOSED CELL PLASTIC FOAMS

The problem of estimating CFC emissions is complicated considerably by the fact that the CFC contained in a nonaerosol product may not be emitted until long after product manufacture. When lagged emissions are a significant phenomenon, the level of CFC emissions at any point in time is a function not only of current production levels, but of the age distribution of the entire CFC stock in the economy. Consequently, post-manufacturing emission characteristics must be modeled if reliable estimates of CFC emissions are to be produced.

This appendix presents the simulation model used to estimate emissions from CFC blown closed cell foams. The appendix first presents the model in a general mathematical form. This is followed by a discussion of the numerical values of important parameters in the emissions process of closed cell foam products.

## THE SIMULATION MODEL

The model simulates CFC emissions in two steps. First, manufacturing and post-manufacturing emissions functions are used to calculate emissions over time from CFC blown foams produced during a given period. This procedure transforms observations (or projections) of CFC use in a single time period into time series estimates of vintage-specific emissions, and is repeated for all vintages of foam output. The second step in the simulation model involves the summation of emissions over all vintages to derive the relevant CFC emissions profile.

Consider the output of a closed cell foam product during an arbitrary single year. This foam will consume a certain amount of CFC during its production. Over the life cycle of this vintage of foam output, the CFC blowing agent consumed during manufacture can be released to the atmosphere during either product manufacture, normal use, or disposal.

Emissions during the earliest stage of product life are the easiest to deal with. Manufacturing emissions, including storage and handling losses, depend upon current CFC use levels only. Moreover, no evidence suggests that the rate of manufacturing emissions varies with the level of foam output. Therefore, manufacturing emissions from foam of vintage t, $m_t$, can be specified as a linear, proportional function of CFC use, $CFC_t$, as in Eq. (F.1) where $\delta$ denotes the manufacturing emissions rate as a fraction of CFC use.[1] (Table F.1 contains the definitions of all the variables of the emissions process.)

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[1] For the closed cell foams, annual CFC consumption is not directly observable, and CFC use is estimated by: $CFC_t = cF_t$ where $F_t$ denotes total CFC blown foam output and c is the average CFC content of a pound of CFC blown foam output.

Table F.1

DEFINITION OF VARIABLES IN THE CLOSED CELL FOAM EMISSIONS PROCESS

| Variable | Definition |
|---|---|
| $CFC_t$ | Total CFC use of foam produced in year t. |
| $\delta$ | Fraction of CFC use lost during manufacture. |
| $m_t$ | Total manufacturing losses during year t. |
| $B_t$ | CFC "bank" immediately after manufacture. |
| $\Omega(a)$ | Normal use emissions function. |
| $N(a)$ | Cumulative normal use emissions as fraction of initial CFC bank through $a^{th}$ period of foam life. |
| $\phi(a)$ | Product disposal probability density function. |
| $D(a)$ | Cumulative product disposals as fraction of initial production in $a^{th}$ period of foam life. |
| $R(a)$ | Fraction of initial foam output remaining in the stock in $a^{th}$ period of foam life. |
| $n_t(a)$ | Normal use emissions from foam of vintage t during $a^{th}$ period of foam life. |
| $d_t(a)$ | Disposal emissions from foam of vintage t during $a^{th}$ period of foam life. |
| r | Fraction of remaining CFC emitted at disposal. |

$$m_t = \delta \cdot CFC_t \tag{F.1}$$

The amount of CFC that is not emitted during manufacture enters the CFC bank, $B_t$, which is represented symbolically in Eq. (F.2).

$$B_t = (1-\delta)\, CFC_t. \tag{F.2}$$

Most of the CFC blowing agent used in closed cell foams leaves the production facility embodied in the cellular structure of the foam—i.e., it enters the bank and, therefore, the post-manufacturing emissions process.

The post-manufacturing emissions process involves two distinct underlying functions. The first of these is the normal use emissions function, $\Omega(a)$, which predicts the rate at which CFC diffuses from a foam product over time (the symbol "a" denotes foam age). For closed cell foams we have:

$$\int_0^{\infty} \Omega(a)\, da = 1.0 \tag{F.3}$$

Equation (F.3) assumes that eventually the normal use emissions process would result in the complete emission of any CFC banked during production. Cumulative normal use emissions (as a fraction of $B_t$) by the a-th period of product life, N(a), are given by Eq. (F.4):

$$N(a) = \int_0^a \Omega(a)\, da \tag{F.4}$$

where $0 \leq N(a) \leq 1.0$.

The second important underlying function of the post-manufacturing emissions process is the probability density function for product disposal. This function describes the fraction of original foam output disposed during any period in the life cycle of the foam vintage. If we denote the product disposal p.d.f. as $\phi(a)$, then:

$$\int_0^\infty \phi(a)\, da = 1.0 \tag{F.5}$$

Cumulative product disposals, as a fraction of the initial output level, and the fraction of end-products surviving to the a-th period of foam life are given by Eqs. (F.6) and (F.7), respectively:

$$D(a) = \int_0^a \phi(a)\, da \tag{F.6}$$

$$R(a) = 1 - D(a). \tag{F.7}$$

Equation (F.2), which defines the amount of CFC entering the post-manufacturing emissions process, and the underlying disposal and normal use functions of Eqs. (F.4), (F.6), and (F.7) provide an information base that is sufficient for the estimation of CFC emissions from a vintage of foam throughout its life cycle. During any given period following product manufacture, both disposal emissions and normal use emissions will occur. However, it is important to note that emissions during these stages of foam life are not independent. The level of normal use emissions determines the amount of CFC contained in the cells of a foam product when it is finally scrapped and, therefore, is a determinant of the level of disposal emissions. Similarly, the level of normal use emissions depends upon the size and age distribution of the existing foam stock. Since the characteristics of the foam stock are a function of the disposal p.d.f., the disposal function also affects the level of normal use emissions.

Normal use emissions from foam of vintage t during the a-th period of product life, $n_t(a)$, are represented in Eq. (F.8):

$$n_t(a) = B_t \cdot R(a) \cdot (N(a) - N(a-1)). \tag{F.8}$$

For most products, it is convenient to define the length of a single period of product life as one year. Then, Eq. (F.8) states that normal use emissions during the a-th year of foam life equal the CFC bank of this vintage of foam, adjusted for foam scrappage prior to that time, times an annual normal use emissions function.

Disposal emissions during the a-th year of life of a foam vintage produced in year t are given by Eq. (F.9):

$$d_t(a) = B_t \cdot (R(a-1) - R(a)) \cdot (1-N(a)) \cdot r \tag{F.9}$$

where r is defined as the fraction of remaining CFC emitted at disposal. Equation (F.9) can be usefully broken down into several components. The first component, $B_t\,(R(a-1) - R(a))$, shows how much CFC would be contained in disposed products if normal use emissions are ignored. The factor $(1 - N(a))$ adjusts this quantity for cumulative normal use emissions through the a-th year of foam life and results in an estimate of potential disposal emissions. However, the disposal of a CFC blown foam does not necessarily imply that all the CFC remaining in the product is released to the atmosphere. Consequently, actual disposal emissions equal the amount of CFC contained in disposed products times the fraction of that CFC assumed lost to the atmosphere.

Equations (F.1), (F.8), and (F.9) completely summarize the emissions cycle of any vintage of foam output. The amount of CFC emitted during any period from the foam vintage, $e_t(a)$, equals the sum of emissions from each stage of foam life. At the time of production (i.e., $a = 0$), emissions are simply equal to $m_t$. After the foam leaves the plant (i.e., when $a > 0$), emissions equal the sum of normal use and disposal emissions. Thus,

$$e_t(a) = \begin{cases} \delta \cdot CFC_t & \text{if } a = 0 \\ B_t\,[R(a)(N(a) - N(a-1)) + (R(a-1) - R(a))\,(1-N(a)) \cdot r] & \text{if } a > 0 \end{cases} \tag{F.10}$$

Equation (F.10) completely describes CFC emissions from a single vintage of foam. Of course, emissions at any point in time emanate not from a single vintage of foam, but from many vintages. As a result, the second general step in the simulation model sums the emissions from all existing vintages to estimate total emissions during a given period. Mathematically, this summation merely uses the fact that the age in year T of foams produced in year t is $(T - t)$. Consequently, total emissions in year T, $E_T$, can be estimated by substituting $a = T - t$ in Eq. (F.10) and summing over all vintages:

$$E_T = \sum_{t=0}^{T} e_t(T-t) = m_T + \sum_{t=0}^{T} n_t(T-t) + \sum_{t=0}^{T} d_t(T-t) \tag{F.11}$$

The calculations described by Eq. (F.11) can be repeated for emissions during any year. The final outcome is a set of estimated annual emissions levels, $E_T$, where T ranges from the first year the closed cell foam was produced commercially (about 1960 and 1965 for rigid urethane and extruded PS board, respectively) to projected emissions levels out to 1990. This set of annual emissions levels constitutes the goal of the simulation model: an emissions profile for the type of closed cell foam under consideration.

## PARAMETER VALUES

To employ the simulation model, it is necessary to specify equations for CFC use and for CFC emissions during product manufacture, normal use, and disposal. The specification of these equations differs significantly depending upon the type of closed cell foam and final product under consideration. For rigid polyurethane, the simulation model distinguishes nine final product markets, which consume foam produced by five production processes.[2] In addition, the model was used to simulate emissions from extruded polystyrene board consumed in the residential and commercial construction markets.

Table F.2 presents CFC use rates as a percentage of foam weight for each rigid urethane production process. With the exception of frothed foam, the estimates refer exclusively to CFC-11. For frothed pour in place (PIP) foams, CFC-12 accounts for about one-quarter of CFC use (or 4.5 percent of foam weight) with CFC-11 accounting for the remainder. Estimates of frothed foam output are based on data in Table F.3, which presents available evidence on the share of PIP foam that is produced with a frothing process. During recent years, the prevalence of the frothing process has declined significantly, particularly in the home refrigeration markets. While home refrigerators and freezers were formerly the most significant markets for frothed foam, industry sources estimate that only about 10 percent of the foam insulation used in these markets is now frothed.

Table F.2

CFC USE AS PERCENTAGE OF FOAM WEIGHT BY PRODUCTION PROCESS

| Production Process | CFC Use Rate (%) |
|---|---|
| Slabstock | 14.1 |
| Laminated boardstock | 12.1 |
| Field spray | 12.3 |
| Pour in place, nonfroth | |
| Refrigeration | 13.4 |
| Other | 12.1 |
| Pour in place, froth[a] | 16.5 |

SOURCES: Midwest Research Institute (1976b), and industry sources. All estimates include CFC released during storage and handling.

[a] Includes about 4.5 percent CFC-12 and 12.0 percent CFC-11.

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[2] The final product markets are commercial, residential, and industrial construction; home refrigerators, home freezers, and commercial refrigeration; transportation; packaging; and flotation. The production processes are rigid slabstock; laminated boardstock; field spray; pour in place, nonfroth; and pour in place, froth.

## Table F.3

### FROTHED RIGID URETHANE AS PERCENTAGE OF POUR IN PLACE FOAM

| Market | Froth as Percentage of PIP Foam |
|---|---|
| Construction | 23.2 |
| Home refrigeration[a] | 10.0 |
| Commercial refrigeration | 60.0 |
| Transportation | 56.7 |
| Packaging | 0.0 |
| Marine/flotation | 50.0 |

SOURCES: Midwest Research Institute (1976b), p. IV-33, and industry sources.

[a] Includes home refrigerators and freezers.

With the exception of some nonurethane foams, manufacturing emissions rates for the closed cell foams are typically a small fraction of CFC use. The manufacturing emissions rates employed in the simulation model for rigid urethanes are presented in Table F.4. For field spray and PIP foams, these emissions rates are based on data from Midwest Research Institute and sources in the refrigeration industry, the largest consumers of PIP foams.[3] Estimates of slabstock losses during manufacture are considerably lower than previous estimates, reflecting information from numerous industry sources. In contrast, the manufacturing emissions rate used for laminated boardstock is significantly higher than previous estimates, reflecting more accurate information on the amount of trimming that occurs in this production process.[4] Finally, for extruded PS board insulation, average manufacturing losses are assumed to be 10 percent of CFC use.

Normal use emissions represent the most complicated stage of the closed cell foam emissions process. Because the thermal efficiency of foam insulation depends upon the CFC content of the foam cells, the k-factor of these insulation products is closely related to the normal use emissions function. Consequently, estimates of the normal use emissions function are based on the theoretical literature on k-factor degradation (or the aging process) in foam insulation[5] and on recent information from industry sources, which are investigating the aging process of closed cell foams.

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[3] Midwest Research Institute (1976b), Chapter IV, and statement of Frank Schumacher in EPA (1977a), p. 36.

[4] Statement of Gerald Reynolds in EPA (1977a), p. 259. These losses occur almost exclusively when the foam product is trimmed to its final dimensions and several major producers are actively seeking ways to reduce trim (and CFC) losses. However, in this report the 9.0 percent estimate is used throughout the period of study.

[5] See, for example, Norton (1967), Ball et al. (1970), and Von Schmidt (1968). For recent work on this issue, see Ball et al. (1978).

## Table F.4

### MANUFACTURING EMISSIONS AS A PERCENTAGE OF CFC USE BY PRODUCTION PROCESS

| Production Process | Manufacturing Emissions Rate (%) |
|---|---|
| Slabstock | 10.2 |
| Laminated boardstock | 9.0 |
| Field spray | 10.9 |
| Pour in place, nonfroth | 11.1 |
| Pour in place, froth | 17.8 |

SOURCES: Midwest Research Institute (1976b), EPA (1977a), and industry sources.

Available evidence indicates that the cumulative normal use emissions function for rigid polyurethane and isocyanurate foams can be closely approximated by a Weibull distribution. That is,

$$N(a) = 1 - e^{-ba^{c}}$$

where b and c are the shape and scale parameters, respectively. For nonurethane closed cell foams, several industry sources indicate that the corresponding equation is an exponential function, a special case of the above specification with $c = 1$.

As discussed in Sec. III.C, the actual parameters of N(a) will vary dramatically, depending upon the physical characteristics of the foam product. Table F.5 summarizes the diversity of normal use emissions functions used in the simulation model for rigid urethane and isocyanurate foams. In all cases, the functions are constrained to have the same general shape with $c = 0.615$.[6] The value of the scale parameter determines the rate at which normal use emissions occur and reflects the assumed average thickness and cladding characteristics of foam products in the market under consideration.[7]

For markets in which adequate information on foam thickness is unavailable, a default average foam thickness of 2.0 inches is assumed, implying normal use emissions half-lives of 60 years for unclad foams and 240 years for clad foams.[8] However, in several important markets, available evidence leads to alternative assumptions regarding average foam thickness. Laminated boardstock is used as a sheathing material in the walls and roofs of buildings. Because of constraints

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[6] This value is based on an analysis of theoretical data contained in Norton (1967).

[7] Mathematically, for two foam samples differing only in foam thickness:

$$\frac{h_1}{h_2} = \left(\frac{t_1}{t_2}\right)^2$$

where $h_i$ and $t_i$ ($i = 1,2$) are the half-life and thickness of the i-th foam sample. To account for the effects of cladding, we assume the half-life of clad foams is four times greater than the half-life of otherwise identical unclad foams. See Sec. III.C.

[8] Equivalently, the scale parameters corresponding to an assumed thickness of 2.0 inches are 0.056 for unclad foams and 0.024 for clad foams.

### Table F.5

### CUMULATIVE NORMAL USE EMISSIONS FUNCTIONS FOR CLAD AND UNCLAD CLOSED CELL FOAMS

| Market | Clad Foams[a] | | | Unclad Foams[b] | | |
|---|---|---|---|---|---|---|
| | Average Foam Thickness (in.) | Half Life[c] (yr) | Scale Parameter[d] | Average Foam Thickness (in.) | Half Life[c] (yr) | Scale Parameter[d] |
| Construction | | | | | | |
| Commercial[e] | 1.25 | 94 | 0.043 | 2.0 | 60 | 0.056 |
| Residential | 0.75 | 34 | 0.080 | 2.0 | 60 | 0.056 |
| Industrial | 2.0 | 240 | 0.024 | 1.5 | 34 | 0.080 |
| Refrigeration | 2.0 | 240 | 0.024 | N.A.[f] | N.A. | N.A. |
| Transportation | 3.0 | 540 | 0.015 | 3.0 | 135 | 0.034 |
| Packaging | N.A. | N.A. | N.A. | 2.0 | 60 | 0.056 |

SOURCE: Based on information from industry sources.

[a] Includes laminated boardstock and pour in place foams.

[b] Includes rigid slabstock and field spray foams.

[c] The half-life is the foam age at which 50 percent of the originally banked CFC has been emitted.

[d] Cumulative normal use emissions functions are of the form $N(a) = 1 - e^{-ba^c}$, where $a$ = foam age, $c = 0.615$ is the shape parameter, and $b$ is the scale parameter.

[e] For clad commercial construction foams, data apply to laminated boardstock only. For pour in place commercial construction foams, average thickness is 2.0 inches, the half life is 240 years, and the scale parameter is 0.024.

[f] N.A. = not applicable.

imposed by standard building designs, these insulating foams are rarely as thick as 2.0 inches. Residential applications of laminated boardstock are dominated by wall sheathing, which varies in thickness from less than 0.5 to about 1.0 inches, and an average thickness of 0.75 inches is assumed for these products. In commercial construction applications, laminated boardstock in roofs is typically thicker (about 1.5 inches), wall thicknesses are comparable to those in the residential sheathing market, and an average thickness of 1.25 inches is assumed. According to an industry source, rigid urethane foam applied on storage tanks and other industrial structures does not often exceed 2.0 inches. Consequently, slabstock and spray foams in industrial applications are assumed to be 1.5 inches thick. Finally, available evidence indicates that foam insulation used in transportation applications generally exceeds 2.0 inches. While foam thicknesses vary in this application and are as high as 6.0 inches,[9] transportation applications are assumed to be 3.0 inches thick on average, implying an extremely long half-life of 540 years for clad transportation foams.

The disposal functions for foam-containing products are summarized in Table

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[9] See, for example, the statement of Royce B. Boykin in EPA (1977a).

F.6.[10] The distributions of product disposal for the construction industry are based on information from the U.S. Bureau of Economic Analysis.[11] These disposal functions are Winfrey distributions, which are utilized by the Department of Commerce in estimating capital stocks. These distributions are bell-shaped, symmetric, and centered over the average lifetimes in Table F.6. Briefly stated, for the nonresidential markets, the first disposals are estimated to occur at 45 percent of the average life and the last occur at 155 percent of the average life. For the residential market, which is assumed to be composed of longer-lived structures on average, disposals begin earlier, at five percent of average life, and end later, at 195 percent of average life.

Table F.6

DISPOSAL FUNCTIONS FOR END PRODUCTS CONTAINING CLOSED CELL FOAMS

| Market | Assumed Distribution | Average Life (yr) | Standard Deviation (yr) |
|---|---|---|---|
| Construction | | | |
| Commercial | Winfrey | 36 | N.A.[a] |
| Residential | Winfrey | 80 | N.A. |
| Industrial | Winfrey | 27 | N.A. |
| Refrigeration | | | |
| Refrigerators | Normal | 17 | 3.0 |
| Freezers | Normal | 20 | 5.0 |
| Commercial | Normal | 20 | 5.0 |
| Transportation | Normal | 10 | 3.3 |
| Packaging | Discrete | 1 | N.A. |
| Marine/flotation | Normal | 15 | 5.0 |

SOURCES: U.S. Bureau of Economic Analysis (1976), IR&T (1979a and 1979b), and industry sources.

[a] N.A. = not applicable.

Disposals are assumed normally distributed for all other product categories except packaging. The average lives of refrigeration products are based on information from industry sources and IR&T. The 10 year average life for transportation foams is based on information regarding truck trailers, and the standard deviation of 3.33 years assumes that the ratio of the standard deviation to the mean life of truck trailers is the same as for truck tractors.[12] The disposal function for packaging is substantively different than that of the other product categories. Packaging applications of rigid urethane involve foaming around items to be transported.

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[10] Table F.6 summarizes the fate only of the final product containing CFC blown foam. Of course, the disposal of the final product does not necessarily imply that all remaining CFC is emitted. However, as a worst case assumption, this report assumes that all remaining CFC is emitted when a product is scrapped (i.e., $r = 1$ for all products).

[11] U.S. Bureau of Economic Analysis (1976), pp. T-3 to T-10.

[12] The 10 year average life for truck trailers is based on the statement of Royce B. Boykin (EPA, 1977a). The ratio of the standard deviation to the average life of truck tractors is based on vehicle registration data collected by IR&T.

While precise information on the fate of these foams is not available, it is reasonable to assume that they are very short-lived relative to other rigid urethanes. Therefore, a discrete disposal function has been used for packaging, which assumes that 50 percent of these foams are disposed during the first year of foam life and 50 percent during the second year.[13]

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[13] A similar disposal function is assumed for short-lived foam-bearing products in McCarthy et al. (1977).

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